ANALYSIS OF THE SHALLOW SUBSURFACE FLOW PROCESS IN THE GEORGIA COASTAL PLAIN

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ANALYSIS OF THE SHALLOW SUBSURFACE

FLOW PROCESS IN THE GEORGIA COASTAL PLAIN

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

SUMMARY

The role of the shallow subsurface flow process over a watershed is a subject of much speculation. This research focused on gaining a better understanding of the macroscale shallow subsurface flow process in the Georgia Coastal Plain. The study area is located in south-central Georgia near Tifton, Georgia.

Two types of field experiments were designed to provide data for the study. First, a series of rainfall simulation experiments on small field plots were designed to describe the relative ability of various soils and topographic locations to produce subsurface flow. The second field experiment was designed for formulating and testing a subsurface flow model. For this experiment a highly instrumented watershed under natural rainfall was used.

For the soils studied, an average of about 42% of the applied rainfall became subsurface flow, with the final infiltration rate varying between 1 in/hr and 3 in/hr. The infiltration rates and shallow subsurface flow volumes illustrate a consistent relationship with soil topographic groupings classified as upland, middle, and lowland with the upland producing the greatest amount of subsurface flow and the lowland the least. On the 0.849-acre upland watershed shallow subsurface flow accounted for 28.4% of the total precipitation for a 3-year period while surface runoff accounted for only 7% of the total precipitation.

A mathematical model of subsurface flow in the experimental watershed was developed. The model is basically a soil moisture accounting model. It does not contain provisions for handling overland flow or deep seepage. Evapotranspiration is represented by a decay function based on soil moisture, pan evaporation, and a crop growth index curve. Subsurface flow is routed through the soil profile using the hyperbolic tangent as the routing function. Factor analysis was used to divide the watershed into zones both horizontally and vertically according to soil moisture characteristics.

The model has two drainage parameters for each zone, and two scaling parameters for the total watershed. The two drainage parameters have physical interpretation while the scaling parameters are empirical. Relationships are proposed defining the scaling parameters according to watershed characteristics.

The pattern search method of optimization was used to identify the optimum set of parameters for 10 events. On the average, the model produced an average correlation coefficient of 0.89 and an average standard error of estimation of 40 percent. A sensitivity analysis indicated that three parameters were extremely insensitive and could be set at a constant value without significantly changing the model's accuracy. Verification of the model with four independent events indicated the model produced satisfactory results.

The model and data indicated that the major cause of shallow subsurface flow was a combination of a highly permeable surface soil and a semi-impermeable clay layer (B22 horizon) found at the 3- to

4-foot depth. Shallow subsurface flow quantity is essentially a function of the soil water storage above the clay layer. To describe the spatial characteristics of the shallow subsurface flow process the watershed needs to be divided into an upland and lowland area. The upland area acts as a receiver of water which drains relatively fast to the lowland which stores water longer and releases it much slower to streamflow.

Moisture characteristics of the soil indicate horizontal flow begins at a moisture content corresponding to the moisture held at about 0.1 bar tension, and field saturation of sandy soils was determined to be 85% of total porosity of the soil.

CHAPTER I

INTRODUCTION

Efforts to conserve and manage water resources are increasing in importance as evidenced by the activity of many organizations including federal and state governments. In order to design and evaluate land and water management programs, detailed information describing quantity, location, and distribution of water is needed. Since such information is seldom available, it must be estimated. The need for reliable estimation techniques has led to intensive study of the various runoff processes.

Most research in the past has dealt with surface runoff processes. Other flow processes, like shallow subsurface flow, have been ignored or indirectly determined (8, 21, 27, 49). Recent field studies (4, 12, 28, 34, 38, 55) indicated that in many areas the shallow subsurface flow process provides the greatest contribution to streamflow.

Shallow subsurface flow is essentially one of describing the flow of water through a proous medium of soil. One aspect of subsurface flow is infiltration which has been approached by attempting to solve the following equation of flow (2)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial h}{\partial x}\right) + \frac{\partial K}{\partial x} \qquad (1)$$

where

θ = moisture content (%)

t = time (min)

x = position (ft)

h = piezometric head (ft)

K = hydraulic conductivity, a function of moisutre content (ft/min)

Solution of the above equation requires detailed information on the specified hydraulic properties of the soil. Because of the natural variation from point to point, hydraulic properties for field size units are almost impossible to characterize. The hydraulic properties are usually obtained for relatively small samples of soil that can be considered points in the watershed space. The hydraulic properties may vary significantly with respect to depth in the profile and with respect to aerial distribution over the watershed. Thus, the ability to make predictions of shallow subsurface flow over a large area from hydraulic soil properties determined at a few locations in the watershed can range from good to unsatisfactory. Unless an effort is made to gain a better understanding of the macro scale shallow subsurface flow process, this process will continue to be the weak link in many hydrologic models.

Literature Review

During development of subsurface flow concepts, many authors have created their own descriptive name for the process, for example, "throughflow" (28), "translatory flow" (17), "interflow" (2), "return flow" (13), "shallow phreatic flow" (4), and "subsurface stormflow" (12, 24). In this dissertation, the term "shallow subsurface flow" will be used to describe lateral outflow from the soil's upper horizons.

Understanding of the specific mechanisms of shallow subsurface flow have evolved slowly. Hursh and Hoover (22, 24), working in deep permeable forest soils, described shallow subsurface flow as rapid unsaturated flow through open root channels above the water table. Whipkey (56, 57) and Roessel (38) stated that most shallow subsurface flow was through large channels and pores in the soil. Hewlett and Hibbert (18, 19) and Kirby and Chorley (28) suggested that unsaturated flow through the small pores in the soil is the predominant shallow subsurface flow mechanism. Amerman (2) concluded that shallow subsurface flow was saturated flow from perched water tables.

Answers to questions about the significance and nature of shallow subsurface flow have been sought by two methods--controlled field experiments and the "partial area" studies of runoff. For clarity, the following discussion of shallow subsurface flow research will be divided into these two methods.

Controlled Field Experiments

Hewlett (17, 19) was probably the first to perform controlled field experiments to study shallow subsurface flow. He constructed a 3/3/45-foot inclining concrete trough on a 40 percent slope and packed it with southern Appalachian soils. After thoroughly soaking the trough, subsurface flow was measured at the down slope end of the trough for 145 days. Piezometers indicated that the larger pores were substantially emptied during the first 1.5 days. Also, soil moisture and tension measurements revealed that the entire unsaturated soil mass contributed to the shallow subsurface flow throughout the 145 days. After a 5-day transition period, the logarithm of the shallow subsurface flow rate was linearly related to the logarithm of the time from the beginning of drainage.

Whipkey (56, 57) studied shallow subsurface flow on an 8x56-foot forested plot located in east-central Ohio on a highly permeable sandy loam soil with a 28 percent slope. Shallow subsurface flow, generated from artificial rainfall, was collected at depths of 22, 36, 48, and 60 in. Subsurface flow at all depths began 90 to 150 min. after rainfall began, however, 85 percent of the rainfall was stored in the soil for at least 24 hr. The 22- to 36-in. level contributed 80 percent of the total runoff. Flow above the 22-in. depth began when flow from the 22- to 36-in. layer exceeded 15 cm^3/sec. Flow above the 22-in. depth usually responded quickly to the rainfall and peaked at or near the end of the storm and then dwindled to no flow after several hours. Overland flow was significant only after the total profile was saturated.

Dunne (12, 13) studied the shallow subsurface flow mechanism on three small hillside watersheds (.13, .16, and .30 acres) in northeastern Vermont. Subsurface flow was collected at the base of the root zone (2 ft. deep) and at the top of a dense clay layer (6 ft. deep). The 2- to 6-ft. interval never produced more than 0.02 gal/min/ft of hillside. However, when the water table reached the

2-ft. level, subsurface flow increased considerably in magnitude and it responded quickly to rainfall. The maximum discharge from the 0 to 2-ft. interval was 0.12 gal/min/ft of hillside. Subsurface flow from both levels represented only between 1 and 5 percent of the storm runoff for all storms.

Weymen (55) studied subsurface flow in England on a highly permeable sandy loam soil with 21 percent slope. He found that rapid, shallow subsurface flow came from the 10- to 45-cm horizon and was a function of the upslope extent of the saturated conditions. He also concluded that most slow shallow subsurface flow came from the 45- to 75-cm. horizon and was supplied by slow unsaturated drainage from the upper soil mass.

Partial Area Studies

The second method which demonstrates the significance and nature of shallow subsurface flow is based on the partial area concept, also called the "partial watershed contribution," "partial source area," or "unit source area." This concept implies that only a part of the watershed area contributes storm runoff.

Betson (6) examined the "partial area" concept of watershed runoff through a series of mathematical infiltration models developed from data on North Carolina watersheds. He found that a scaling factor included in his infiltration equation produced a closer fit of calculated to observed runoff which he interpreted as implying that contributions to runoff originated from a small (less than 10 percent), but relatively consistent, part of the watershed.

Other hydrologists of the Tennessee Valley Authority (50) further elaborated on Betson's work and concluded that the contributing watershed was a dynamic unit which could vary in size as the storm progressed. They believed that most storm runoff came from the valley floors where soil moisture was highest; and the remainder of the watershed did not contribute directly to storm runoff but acted as a recharge area that absorbed rainfall and allowed it to drain slowly. Hewlett and others (18, 19), considering a steep forested watershed, also proposed a dynamic model that derived its stormflow from the valley areas near the stream with a variable source area located on the lower slopes of the hillsides. Amerman (1, 2), working where runoff was largely controlled by alternating beds of varying permeability, found that runoff-producing areas were distributed randomly on ridge tops, in valley floors, and on valley slopes. Zavodchikov (58) found runoff production was controlled by an effective area which was a function of the general topography of the watershed and the soil moisture.

Ragan (34, 35) studied runoff contributions along a 619-ft length of a second-order stream draining a 114-acre watershed in northeastern Vermont. He found that only a small part of the watershed (between 1.2 and 3 percent) contributed storm runoff. This contributing area was in the form of localized zones rather than uniformly distirbuted along the channels. The size of the contributing area was a function of the storm duration and intensity. Saturated subsurface flow accounted for 36 to 43 percent of the storm runoff, while no significant unsaturated subsurface flow was encountered.

Since the peak rates of the shallow subsurface flow lagged the hydrograph peak at the downstream gaging station, shallow subsurface flow was a more influential contributor to the recession limb than to the rising limb of the stream hydrograph.

Tischendorf (51), who studied shallow subsurface flow on a 60-acre forested watershed in the Georgia Piedmont, observed no surface runoff and concluded that channel precpitation and shallow subsurface flow were the major runoff contributors, accounting for an average of 8 percent of the total precipitation. Through an extensive network of soil moisture tubes and wells, the source area for shallow subsurface flow was found to be dynamic, with a maximum expansion to about 10 percent of the total watershed.

Dunne (12, 13) studied the runoff processes on a 10 acre watershed in northeastern Vermont. The dominant runoff processes were channel precipitation and shallow subsurface flow which emerged from the ground surface and reached the stream as overland flow. However, shallow subsurface flow was the most important contributor to the hydrograph recession. Dunne also concluded that less than 10 percent of the watershed area contributed storm runoff, and this area was dynamic.

In conclusion, both controlled field experiments and partial area studies have shown that shallow subsurface flow plays a major role in the total runoff process in many locations. However, many questions about the macroscale shallow subsurface flow process still remain unanswered.

Objectives

The objectives of this dissertation are [1] to determine the variability of the shallow subsurface flow process over a watershed and relate this variability to soil and topographic conditions and [2] to develop a model for investigating the macro scale shallow subsurface flow process.

Approach

Based on the literature review, site selection criteria were established: [1] The area should have soils with high surface infiltration underlain at shallow depths by an impermeable layer; and [2] be physically different from those areas where subsurface flow has been investigated previously. The Southern Coastal Plain was chosen since it satisfied these criteria.

The specific study area is located in south central Georgia near Tifton, (Figure 1) where the Southeast Watershed Research Center (USDA-ARS) is conducting extensive hydrologic investigations on the 126 square mile Little River Watershed. The area has long, hot, humid summers and short, mild winters with average monthly temperatures ranging from 52°F in January to 81°F in July and August with an average monthly temperature of 66°. The area has occasional freezing weather between the middle of November and the middle of March, with the most severe freezes in January and an average frost-free season of 253 days (7). For the past 49 years, annual rainfall has averaged 47.36 in. A summary of the monthly rainfall amounts for the years 1968 to 1971 is shown in Table 1. The 31-yr. average annual pan evaporation is

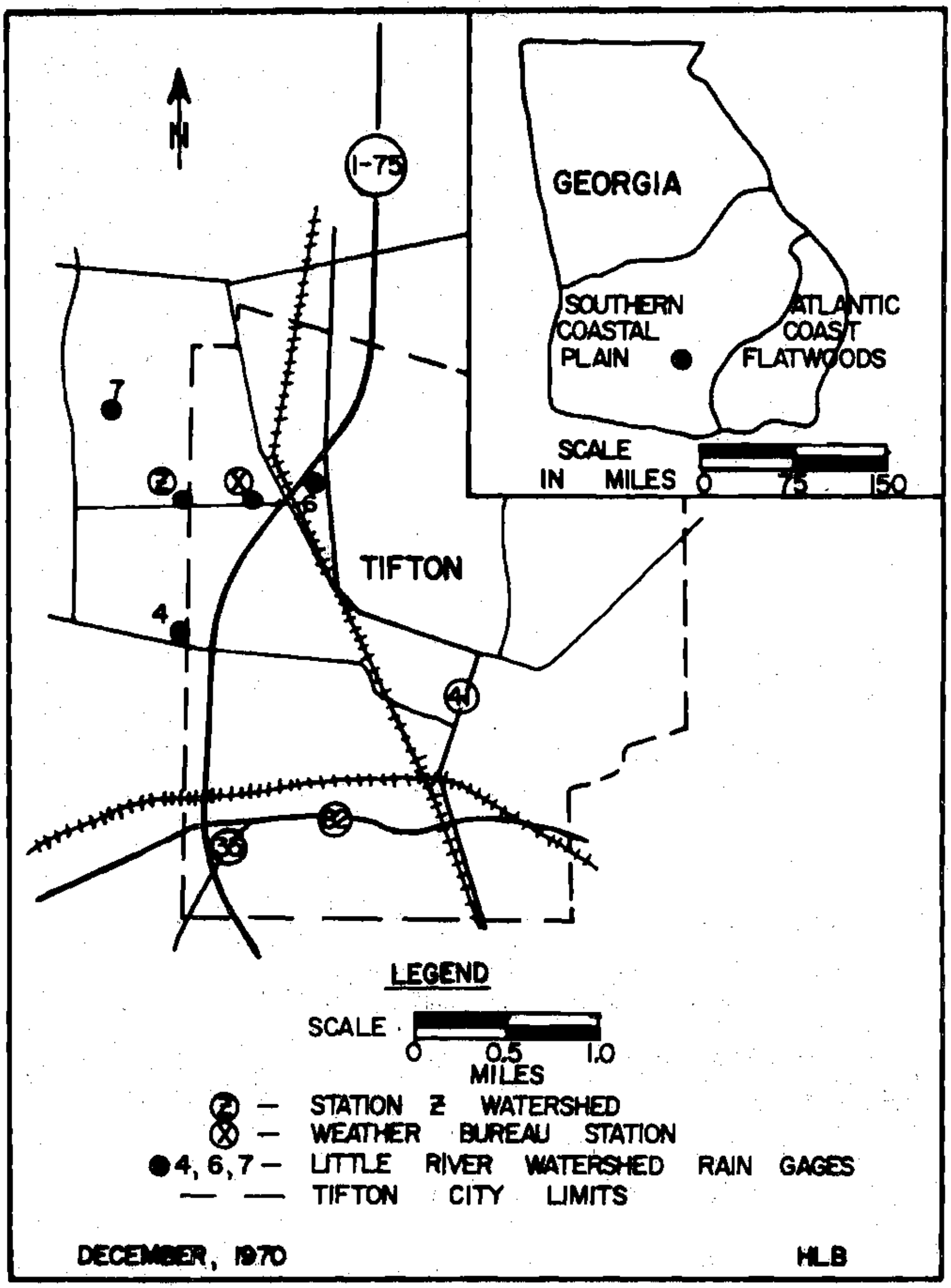

Figure 1. General Location Map

Table 1. Monthly Rainfall Data - Tifton, Georgia, 49-year average and 1969, 1969, 1970, 1971

Month	Rainfall				
	Average 1923-1971	1968	1969	1970	1971
	Inches				
January	3.99	0.42	1.92	2.78	2.55
February	4.00	1.73	3.11	4.78	5.22
March	4.73	3.55	6.34	8.84	5.32
April	4.09	2.31	1.77	1.35	3.72
May	3.51	3.99	5.36	7.52	4.79
June	4.62	1.54	1.44	1.93	6.46
July	6.06	4.61	8.56	6.31	7.61
August	5.25	6.40	7.25	11.08	6.16
September	3.65	0.47	5.28	1.49	0.58
October	1.93	0.96	0.28	4.46	1.82
November	1.97	4.23	0.85	0.74	3.85
December	3.56	5.40	4.23	3.01	5.23
Total	47.36	35.61	46.39	54.29	53.31

56.23 in. with the average monthly values varying from 2.21 in. in December to 7.21 in. in May.

Two types of field experiments were designed to provide the necessary data to achieve the study objectives. First, a series of rainfall simulation experiments on small field plots was designed to study the variability of the shallow subsurface flow process over Little River Watershed and relate the variability to soils and topographic conditions. This type of experiment was chosen because of its economy and effectiveness in covering a wide range of conditions. It was designed so that each major component of the hydrologic budget could be measured or determined. This set of experiments will be referred to as "plot studies."

The second field experiment was designed to develop a model for investigating the macro scale or watershed scale shallow subsurface flow process. For this experiment, a highly instrumented small watershed under natural rainfall was selected. A small watershed, rather than a large one, was chosen so that [1] surface runoff and subsurface flow could be measured separately, and [2] the variability or rainfall, vegetation, and soils could be minimized. This experiment was also designed so that each major component of the hydrologic budget could be measured or determined. This experiment will be referred to as "watershed study."

In combination the two sets of experiments will help to better understand the macro-scale shallow subsurface flow process. The "plot studies" will provide the broad quantitative data needed to expand macro scale concepts developed in the "watershed study" to larger areas. The specific design of each experiment will be described in detail in the next chapter.

CHAPTER II

EXPERIMENTAL PROCEDURE

The experimental procedure for the plot studies will be discussed first, followed by a discussion of the watershed study.

Plot Studies

Location and General Description

The shallow subsurface flow plot studies were conducted on plots in the Little River Watershed. The surface soils of the watershed have a distinct A and B horizon with the texture ranging from a loamy sand to a sandy clay loam in the top 3 to 4 ft. A semipermeable clay layer is usually found at a depth of 3 to 4 ft.

The watershed contains 20 soil series. Ten of these were chosen for investigation. These 10 account for 95 percent of the watershed land area and 91 percent of the land area in Tift County, Georgia. As seen in Table 2, a wide range of physical watershed conditions are represented by these 10 soil series.

Description of Infiltrometer

The Purdue Sprinkling Infiltrometer, as developed by Bertrand and Parr (5) and modified by Dixon and Peterson (10), was used to apply artificial rainfall to the plots. The rainfall is produced from a single full-cone nozzle centered at the top of a 9-ft. tower. The nozzle applies constant rainfall to a circular area of about 100 ft.^{2}. The rainfall rate can be varied from 2.50 in/hr. to greater than 6 in/hr.

Table 2. Watershed Characteristics of the Soil Series

Soil Series	Topographic Position 1/	Dominant Relief (percent)	Most Common Use	Percent of Land Area in Little River Watershed
Cowarts	Upland	5 to 7	Mostly crops; some pasture; little forest.	* 2/
Fuquay	Upland	0 to 5	Forest	15.0
Dothan	Upland	2 to 5	Crops	4.6
Troup	Middle	2 to 5	Crops & forest	0.3
Carnegie	Middle	5 to 7	Crops & forest	4.5
Tifton	Middle	2 to 5	Crops; pasture; little forest.	58.0
Stilson	Middle	0 to 2	Forest; some pasture & crops.	2.5
Leefield	Middle	0 to 2	Forest; some pasture & crops.	1.5
Robertsdale	Lowland	0 to 2	Forest	*
Alapaha	Lowland	0 to 2	Forest	9.0

1/ Horizontal lines divide soils according to topographic position.

2/ * Less than 0.1 percent of the total area.

by exchanging nozzles. All nozzles produce drop size distributions, final drop velocities, and kinetic energy closely resembling that produced by natural rainfall. Nozzle intensities were checked before each run by applying rainfall for 10 min. and collecting the corresponding runoff from a calibration pan. During calibration, the area around the calibration pan was covered with plastic to prevent soil wetting.

A 3.81 x 3.81-ft. metal plot frame was centered on the ground beneath the nozzle and manually driven 2 in. into the ground. Its sides extended 4 in. above ground and a covered flume was attached to the downhill side of the plot. Runoff was carried by a vacuum system from the flume into a collection tank where the volume and rate of runoff were recorded by an automatic water stage recorder. A neutron probe access tube was installed adjacent to the runoff plot on the upslope side to measure soil moisture. These tubes (2-in. O.D. aluminum irrigation tubing) were installed in snug-fitting holes predrilled by a power-driven flight auger. All access tubes were installed at least a month before they were used.

Infiltration Field Procedure

The following procedure was developed to yield infiltration and subsurface flow data under dry and wet soil moisture conditions. For replication purposes the procedure was performed on dual plots at each site.

Artificial rainfall was initially applied at a high intensity (4.45 to 6.73 in/hr.) for a sufficient time to cause a relatively constant surface runoff rate. Rainfall was then stopped for approximately 1 hr., after which it was resumed at a lower intensity (2.64 to 5.17 in/hr.) and continued until a relatively constant runoff rate was obtained. For both applications, 1 to 2-1/2 hr. of rainfall were required to obtain a constant runoff rate. Neutron soil moisture readings were collected at 6-in. intervals to a total soil depth of 36 to 48 in. at the beginning and end of each rainfall event. The depth to which the neutron probe was read depended on the location of the clay layer. Natural conditions were preserved at each site, except where the vegetation was excessively tall. Tall vegetation was cut to a height of 6 to 8 in. Vegatation normally provided between 50 and 80 percent crown cover.

Final infiltration rates were determined by substracting the final surface runoff rate from the rainfall rate. From direct visual observation, it was noted that no subsurface flow was included in the surface runoff measurement. The specific location of all infiltration plots are given in Appendix A along with a summary of the infiltration data.

In summary the plot studies yielded the following data on 10 soils in Little River Watershed: [1] final infiltration rates, [2] shallow subsurface volumes, [3] hydraulic and water holding characteristics of the soil, [4] porosity, and [5] slope and topographic location of the soil. This data base will be used to characterize the variability of the shallow subsurface flow process in Little River Watershed and to relate the variability to soil and topographic characteristics. The watershed study will provide the data needed to develop a model for investigating the macro scale shallow subsurface flow process.

Watershed Study

Location and General Description

The watershed chosen to study subsurface flow under natural rainfall is located in Little River Watershed at Tifton, Georgia, (Figure 1) and is identified as Station Z. This specific watershed was chosen because the Southeast Watershed Research Center, USDA-ARS, is routinely measuring soil moisture, ground water, rainfall, surface runoff, and subsurface flow at the location. The watershed has a surface area of 0.849 acre (Figure 2) with an average slope of 2-1/2 percent and a subsurface area of 0.856 acre (Figure 3) with a 2-percent slope. The surface watershed is bounded by a soil berm, while the subsurface boundary is defined by contours showing the top of the clay layer. The surface elevation of the watershed is approximately 360 ft. above sea level. A general east-west profile of the watershed and surrounding area is shown in Figure 4 which also shows [1] the location of the watershed relative to the nearest stream and [2] the slope changes which were made when a parking lot and building were constructed at the same time the tile drain was installed.

Land Use and Management

The watershed was used as a tobacco fertility plot study area from 1960 to 1963. From 1963 to March 1969, the site remained idle and some weeds and grass developed. On March 10 and 11, 1969, an estimated total of 17,000 lbs. of soil and organic materials which could not be plowed under were removed from the surface of the

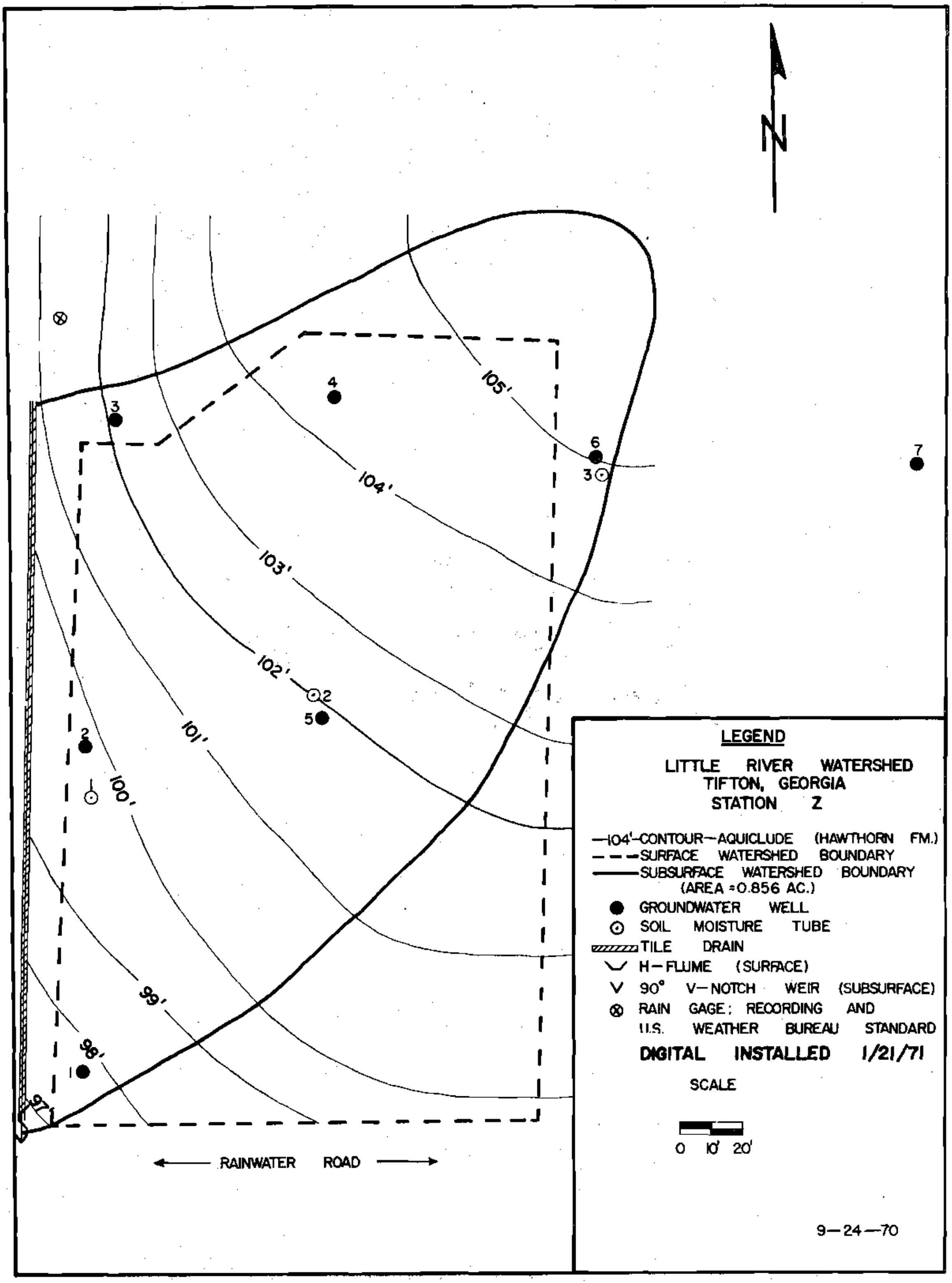

Figure 2. Topographic Map of the Surface Watershed

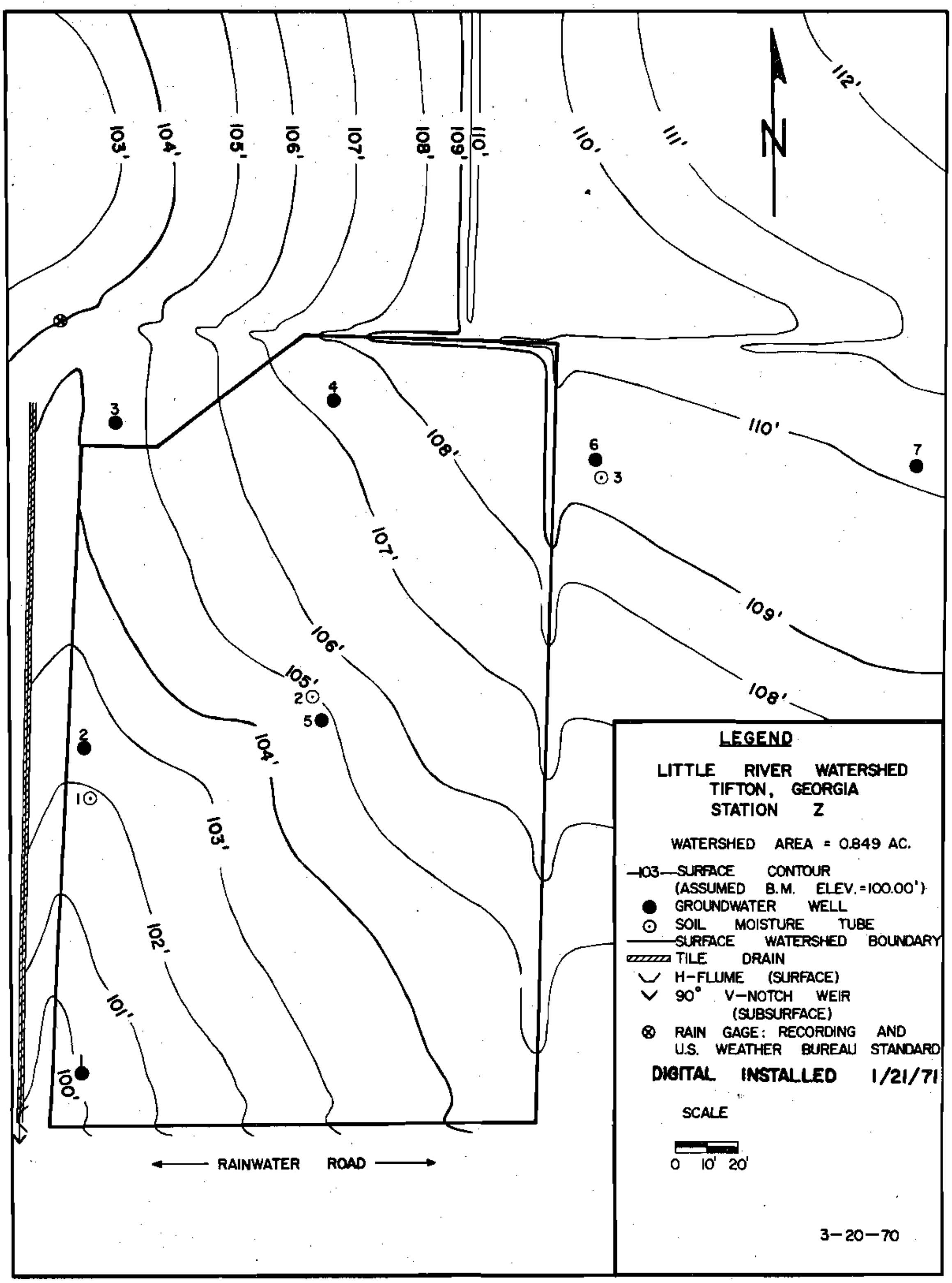

Figure 3. Topographic Map of the Subsurface Watershed

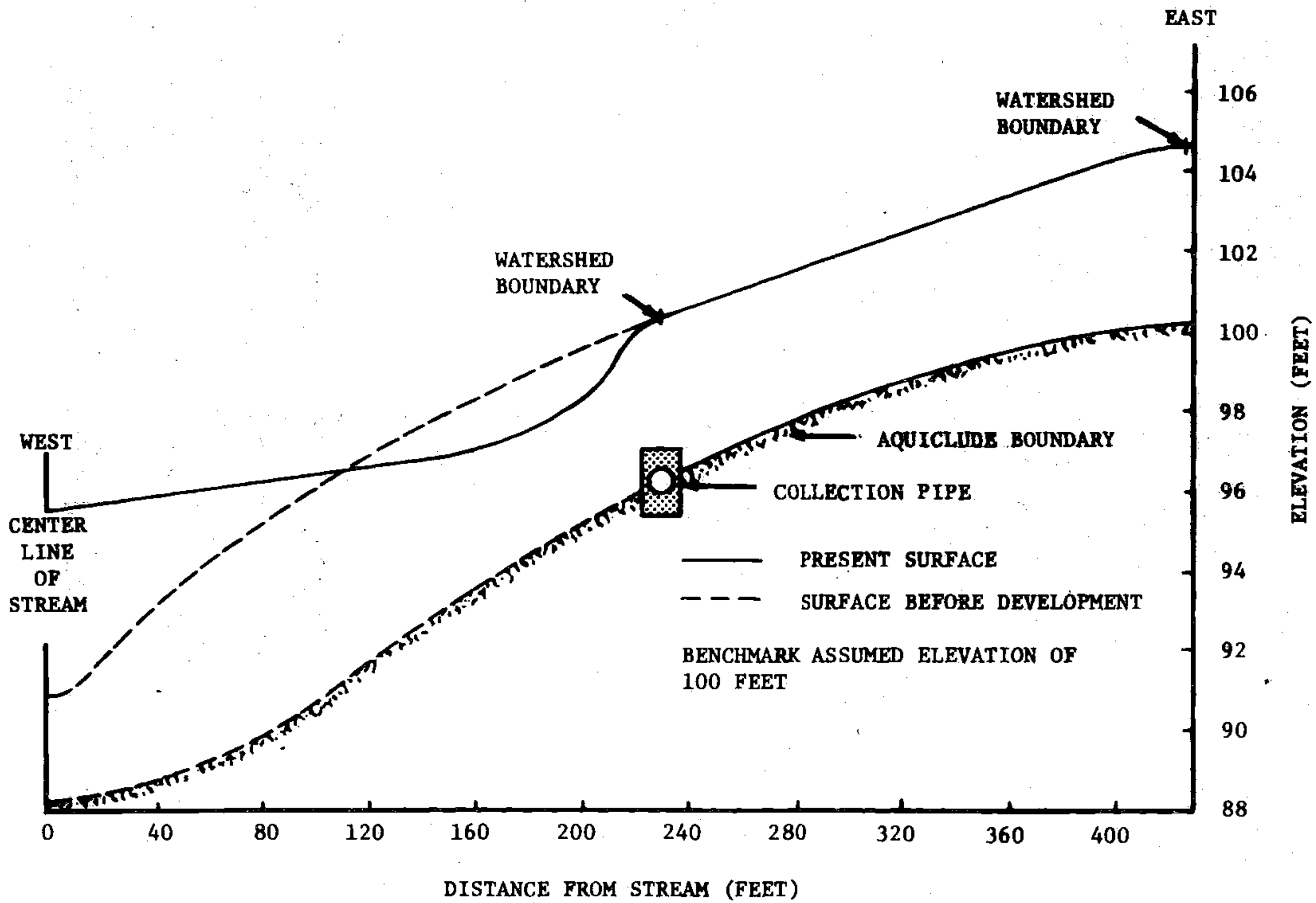

Figure 4. Generalized Profile Map of the Watershed

watershed.[1/] The following cultivation schedule was initiated on the watershed in March 1969.

Disked on March 28, 1969
Redisked on April 4, 1969
Leveled on April 11, 1969
Turned on April 15, 1969
Bedded on April 17, 1969
Corn planted on April 18, 1969
Spiked stage May 1, 1969
No further cultivation
Corn harvested about October 15, 1969
Idle
Disked on March 24, 1970
Redisked on March 25, 1970
Turned and bedded on April 6, 1970
Corn planted on April 10, 1970
Spiked stage April 17, 1970
No further cultivation
Corn harvested on September 17, 1970
Idle
Disked on April 19, 1971
Redisked on April 15, 1971
Turned and bedded on April 16, 1971
Corn planted on April 21, 1971
Spiked stage April 30, 1971
No further cultivation
Corn harvested on October 1, 1971

The above cultivation schedule is common in the Georgia Coastal Plain. The corn was planted in a north-south direction, which is approximately a 45-degree angle to the general slope of the field. A herbicide program was used to control weeds. The part of the subsurface drainage area that extended beyond the surface watershed (Figure 2) remained in a grassed condition.

1/ Personal communication with Loris Asmussen, resident project supervisor

Geology and Soils

The parent geological materials for the surface soil are eolian and fluvial sediments of Pleistocene Age ranging from 3 to 7 ft. thick. The surface soil is classified as a Cowarts sandy loam and varied in texture from clayey sand to sandy clay, generally in a west to east direction (4). A representative soil profile description and corresponding moisture tension data are given in Tables 3 and 4 respectively. Underneath the surface soil lies the Hawthorn Formation of Miocene Age (4), composed of unconsolidated marine and nonmarine sands and clays. A topographic map of the top of the Hawthorn formation is given in Figure 3.

Instrumentation

Rainfall was initially measured by a standard U.S. Weather Bureau rain gage installed in 1967. This gage was measured and emptied after each storm. Rain gages 4, 6, and 7 of the Little River precipitation network were used to distribute the rainfall measured by the standard rain gage. These gages are within a 1.5 mile radius of the study area as shown in Figure 1. On March 27, 1969, a weighing type recording rain gage was installed.

The shallow subsurface flow was intercepted at the lower end on the drainage area by a 240-ft., gravel-packed, 4-in. terra cotta tile drain set in the top surface of the dense sandy clay Hawthorn formation. Subsurface flow from the tile drain flows through a 6 in., 90-degree V-notch weir and is recorded by a binary stage recorder, recording stage to the nearest thousandth of a foot at 5-min. intervals. Appendix B gives the V-notch weir calibration. Subsurface flow instrumentation was installed in June 1968.

Surface runoff was measured by a 1-ft. H-flume installed in June 1969 at the southwest corner of the surface watershed. A detailed calibration of the flume is given in Appendix B. To make the length of surface runoff records comparable with the length of subsurface flow records, the only preinstallation surface runoff event (April 16, 1969) was visually estimated.

Ground water levels were manually monitored by a system of seven 1-in. ground water observation wells drilled into the Hawthorn formation (Figure 3). The frequency of ground water readings was weekly or more often, depending on the magnitude of subsurface flow. Collection of ground water data began on June 1, 1968.

Soil moisture was measured every week or more often, depending on the magnitude of subsurface flow. Measurement depths were 6, 12, 18, 24, 36, 48, and 54 in. below the ground surface for all three access tubes (Figure 2). A Troxler 104-A depth probe with a 241-Am-Be neutron source, 100 mc, and a Troxler 200-B scaler were used to measure soil moisture. The above probe was field calibrated for use in this study and is described in Appendix B. Collection of soil moisture data began on May 27, 1968.

Supplementary data, like soil temperature, air temperatures, pan evaporation, water temperature, wind, and radiation, were collected during the study period by the U.S. Weather Bureau at Georgia Coastal Plain Experiment Station at Tifton, Georgia. This station is located 0.5 mile east of the study area (Figure 1 location X).

Table 3. Representative Soil Profile of Cowarts Loamy Sand

Horizon	Depth (in)	Description
Apcn	0-8	Dark, grayish brown (10YR-4/2) loamy sand; weak fine granular structure; very friable, non-sticky; many small hard iron pebbles 1/8 to 1/2 in. in diameter; many fine roots; strongly acid; abrupt smooth boundary.
B1tcn	8-14	Yellowish brown (10YR-5/8) sandy loam; weak medium granular structure; very friable, non-sticky; many small hard iron pebbles; fine roots common; strongly acid; clear wavy boundary.
B21cn	14-37	Yellowish brown (7.5YR-5 /8) sandy clay loam; moderate medium subangular blocky structure; friable, sticky; small hard iron pebbles common; few fine roots mostly in upper part; very strongly acid; gradual wavy boundary.
B22tcnpl	37-50	Yellowish brown (10YR-5/6) sandy clay loam with common and medium distinct mottles of light yellowish brown (2.5YR-6/4) and red (2.5YR-4/8); moderate medium subangular blocky structure; firm, sticky; few hard and soft iron pebbles; soft plinthite; very strongly acid; gradual wavy boundary.
B23tpl	50-65	Reticulately mottled, yellowish brown (10YR-518), light gray (10YR-7/1), red (2.5YR-418), and strong brown (7.5YR-5/8 sandy clay loam; moderate medium subangular structure; few patchy clay films on red faces; firm, sticky; soft plinthite; very strongly acid.

Table 4. Representative Moisture Characteristics of Station 2

Horizon classification.	Depth (in)	Volume Percent Water Retained Tension (Bars) 0.1	0.3	0.6	3.0	15.0	Bulk Density (g/cc)	Total Pores %
Apcn	0-8	15.1	9.4	5.7	5.5	2.9	1.64	34.6
B1tcn	8-14	18.6	14.4	13.2	10.5	4.6	1.66	35.8
B21cn	14-37	27.5	21.1	17.0	14.3	8.4	1.62	36.9
B-2tcnpl	37-50	28.3	22.1	18.8	17.2	5.5	1.60	39.5
B23tpl	50-65+	29.2	24.0	21.4	16.2	6.9	1.72	40.6

Conductivities	Hole 1 1/	Hole 2 2/
Average Horizontal Conductivity (ft/hr)		
0-12 in zone	1.42	2.18
12-36 in zone	1.06	1.48
Average Verticial Conductivity (ft/hr)		
0-12 in zone	0.17	0.16
12-36 in zone	0.40	0.31
clay layer	0.002	0.002
Average Voids Drained		
Inches of Water in 15 min.		
0-12 in zone	1.03	2.04
12-36 in zone	1.42	2.46
Inches of Water in 15 hr.		
0-12 in zone	1.18	2.28
12-36 in zone	2.69	3.52
Maximum Water Holding Capacity (inches of water)		
0-12 in zone	3.84	3.52
12-36 in zone	10.06	8.88
Maximum Water Holding Capacity Under Field Conditions[3] (inches of water)		
0-12 in zone	3.27	3.00
12-36 in zone	8.55	7.55

1/ Hole 1 located near soil moisture tube 1 (Figure 2-1)
2/ Hole 2 located near well No. 6 (Figure 2-1)
3/ 85 percent of maximum water holding capacity

CHAPTER III

WATER BALANCE

In Chapter I, the objectives of the research were outlined. The first objective was to determine the variability of the shallow subsurface flow process in Little River Watershed and relate this variability to soil and topographic conditions. The purpose of this chapter is to describe how this objective was accomplished. The basic procedure was to determine the value of each term in the water balance equation for a variety of conditions. The water balance used for the plot and watershed studies is represented by the equation:

$$P = SR + SS + ET + SM + DP \qquad (2)$$

where,

P = precipitation

SR = surface runoff

SS = shallow subsurface flow

ET = evapotranspiration

SM = change in soil moisture storage

DP = deep percolation

All terms in equation 2 are defined as a volume per time interval. Also, shallow subsurface flow is defined as lateral outflow from the soil's upper horizons. Although precise evaluation of the individual terms of equation 2 is difficult, the relative importance of each can be determined.

Application of artificial rainfall to plots yielded from four to ten separate final infiltration rates for each soil series. The numerical average of these final infiltration rates according to soil series is shown in Table 5. These infiltration rates are extremely high (between 1 and 3 in/hr), indicating a major portion of all rainfall will infiltrate. This establishes a potential for subsurface flow as the primary contributor to streamflow.

A water balance, using equation 2, was performed on each rainfall event to determine the relative ability of the soils listed in Table 2 to produce subsurface flow. Surface runoff was measured directly. The change in soil moisture storage was determined by substracting the soil moisture in the profile before each rainfall event from the soil moisture in the profile after each rainfall event. Since only periods of rainfall were considered and the rainfall simulator was enclosed, evapotranspiration was negligible. Also, laboratory hydraulic conductivity analyses of samples from the clay layer indicated negligible deep percolation because the maximum transmission rates of the layer were only of the magnitude of 0.005 in/day. Therefore, any rainfall not accounted for as surface runoff or a change in soil moisture storage was assumed to be lateral shallow subsurface flow. The shallow subsurface flow quantities were averaged for each soil series and are listed (Table 5) as percent of rainfall according to dry and wet initial conditions. The relative volumes of shallow subsurface flow from the various soils studied is demonstrated by the percentage values. For all of the soils studied, an average of 41.65 percent of the applied rainfall became shallow

Table 5. Infiltration and Subsurface Flow Characteristics of Soil Series

Soil Series	Final Infiltration Rates (in/hr) 1/	Computed Subsurface Flow 2/ % of Rainfall	
		Dry	Wet
Cowarts	2.92	62.2	74.4
Cowarts (Z) 3/	2.85	40.1	61.6
Fuquay	2.62	52.6	67.9
Dothan	3.01	32.6	59.9
Troup	2.03	28.9	40.2
Carnegie	2.38	31.9	42.8
Tifton	2.01	35.2	54.9
Stilson	2.21	29.3	48.3
Leefield	2.20	29.5	51.7
Robertsdale	1.03	17.4	20.0
Alapaha	0.98	15.3	18.9
	Average	34.1	49.2

1/ Southeast Watershed Research Center, "Infiltration Study of Soils in Tift County, Georgia - 1969," Athens, Georgia, unpublished report, 1970.

2/ Dry indicates first infiltration run; wet indicates second infiltration run.

3/ (Z) Refers to Station Z Watershed.

subsurface flow. Table 5 shows a consistent relationship between soil topographic groupings, classified as upland, middle, and lowland, and infiltration rates and subsurface flow volumes, with the upland producing the greatest amount of shallow subsurface flow and the lowland the least.

A water balance, using equation 2, was performed on Station Z watershed for the 3 yr. period from October 1968 to October 1971. Rainfall for the period was 153.68 in. which was 11.60 in. above normal. Combined surface runoff and shallow subsurface flow for the period was 54.46 in. In those cases where visual observations were made, no subsurface flow was included in the surface runoff measurement at Station Z. Monthly distribution of precipitation, shallow subsurface flow, and surface runoff are illustrated in Figure 5.

Surface runoff was 10.75 in. which accounted for 7 percent of the total rainfall. A total of 86 surface runoff events[1/] occurred on 73 days during the 3-yr period. The total duration of surface runoff was only 3.36 days. The average duration of a surface runoff event was 56 min. with a range between 15 and 326 min. Surface runoff occurred in all months, except November, with the most prominent events being in July and August. The volume of surface runoff events ranged between 0.0001 and 0.70 in. with an average of 0.133 in.

1/ Event is the occurrence of flow beginning and ending with zero flow.

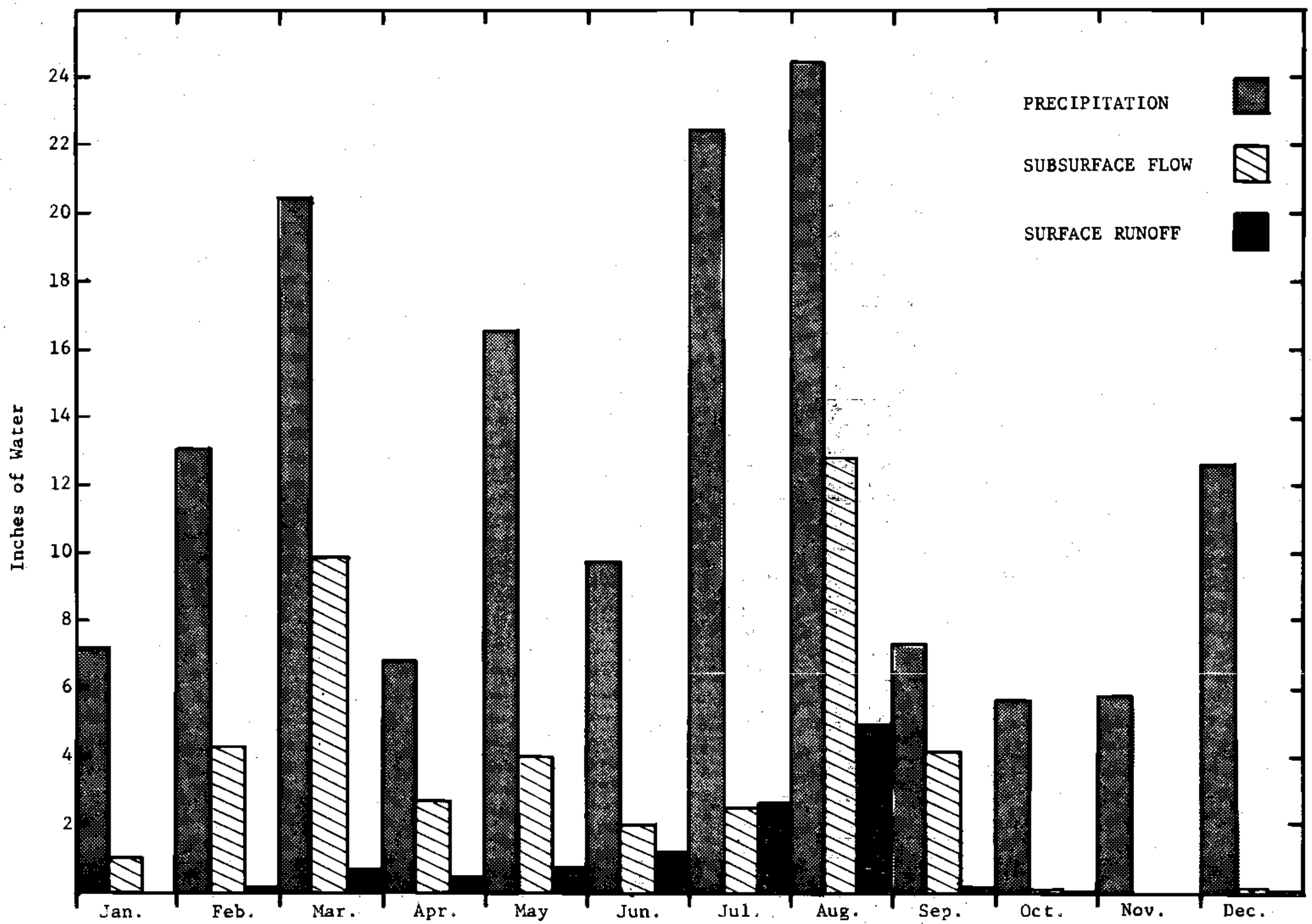

Figure 5. Monthly Distribution of Precipitation Subsurface Flow and Surface Runoff

Measured shallow subsurface flow for the period of study was 43.71 in. which accounted for 28.44 percent of the total rainfall. Shallow subsurface flow events totaled 27 with a total duration of 308 days or 28.13 percent of the 3-yr. period. The average event duration was 11.4 days with a range between 0.8 and 46.2 days. Shallow subsurface flow occurred in all months except November, with March and August as the most prominent months.

As previously stated, laboratory hydraulic conductivity analyses of the clay layer indicated that under saturated conditions the maximum transmission rates of the layer would be 0.005 in/day or 5.04 in. for the 3-yr. period. This represents 3.28 percent of the total rainfall. The ground water observation wells indicated that 64 percent of the time no water table existed above the clay layer. Presumably, the clay layer only transmitted water at its saturated conductivity rate when there was a water table above it. As a result, only 1.81 in. of water would be transmitted during the 3-yr. study period (1.18 percent of rainfall).

Since all the components except evapotranspiration were measured or estimated, equation 2 can be solved for evapotranspiration. It was determined that evapotranspiration accounted for 97.20 in. of water or 63 percent of the rainfall for the 3-yr. study period. The distribution of evapotranspiration with time was determined using the soil moisture measurements which were approximately a month apart. This distribution is presented in Table 6 for the October 1968 to October 1970 period. Some of the evapotranspiration values in Table 6 were inconsistent which was attributed to the neutron soil moisture measurement error (Appendix B).

Table 6. Water Balance, Station Z (October 1968 - October 1970)

Date	Rainfall Less Surface Runoff	Shallow Subsurface Flow	Soil Moisture Storage Change	Evapotranspiration Total	Evapotranspiration Daily
		Inches			
10/4/68	0.96	0.00	0.06	0.90	0.03
11/1/68	6.58	0.04	2.21	4.33	0.12
12/6/68	3.32	0.50	0.18	2.64	0.09
1/3/69	1.53	0.28	-0.11	1.36	0.06
1/27/69	3.17	1.17	-0.19	2.19	0.07
2/28/69	6.51	4.30	-0.03	2.24	0.07
4/2/69	1.62	0.13	-0.89	2.38	0.08
5/2/69	4.87	1.34	-0.48	4.01	0.12
6/5/69	9.15	1.13	1.11	6.91	0.12
8/1/69	9.31	7.64	-0.29	1.38	0.06
9/2/69	4.27	2.62	-0.42	2.07	0.07
10/3/69	0.20	0.00	-1.04	1.24	0.04
11/6/69	0.59	0.00	-0.60	1.19	0.04
12/4/69	6.31	0.17	1.45	4.69	0.13
1/8/70	3.07	0.49	0.08	2.50	0.09
2/4/70	3.12	1.62	-0.32	1.82	0.06
3/5/70	7.38	4.39	0.81	2.18	0.08
4/2/70	0.98	1.55	-1.85	1.26	0.04
5/1/70	7.86	3.04	0.61	4.21	0.10
6/12/70	2.76	0.06	0.73	1.97	0.07
7/9/70	3.22	0.00	-0.40	3.62	0.13
8/6/70	8.77	5.95	0.23	2.59	0.09
9/3/70	1.27	0.64	-1.29	1.92	0.06
10/4/70					

Reportedly, between 25 and 35 percent of the annual precipitation in the Georgia Coastal Plain becomes streamflow (29, 42). The average runoff for Station Z (35.44 percent of annual precipitation) compares favorably with the reported values. The Station Z totals are on the high end of the range; this is partly because the precipitation for the study period was about 11 in. above normal. The specific soils and vegetation at Station Z might also cause the Station Z runoff totals to be high (Table 5). The favorable comparison points out that Station Z is not a unique situation. Also, comparison of surface runoff and shallow subsurface flow quantities clearly demonstrates that shallow subsurface flow is the major process for Station Z.

The results of the plot studies performed on Station Z watershed (Cowarts Z) under various moisture conditions indicated that between 40.1 and 61.6 percent of the applied rainfall became shallow subsurface flow. These values bracket the average shallow subsurface flow event (54 percent of the event precipitation) for Station Z under natural rainfall. This reinforces the validity of the plot studies in demonstrating the relative ability of the various soils to produce shallow subsurface flow.

In conclusion, the plot studies, and the watershed study, indicate that the shallow subsurface flow process was the predominant flow process in the plot and watershed studies. The major cause for shallow subsurface flow in Little River Watershed is a combination of high surface permeability and a semi-impermeable clay (B22 horizon) at a 3 to 4 foot depth.

A relationship between soil topographic groupings, classified as upland, middle and lowland, and subsurface flow volumes and infiltration rates was determined for Little River Watershed soils. The upland soils produced the greatest amount of shallow subsurface flow (56% of the applied rainfall) and the highest average final infiltration rates (2.85 in/hr) while the lowland soils produced the least amount of shallow subsurface flow (18% of the applied rainfall) and the lowest average final infiltration rates (1.00 in/hr).

CHAPTER IV

MODEL FORMULATION

This chapter and the next chapter will deal primarily with the second objective of this thesis, the development and verification of a model to investigate the macro scale shallow subsurface flow process. This chapter will discuss the hydrologic cycle according to the scheme shown in Figure 6. Basically, precipitation is routed through three storage compartments: [1] Interception and depression storage; [2] Soil moisture storage, and [3] Ground water storage. Outputs from the compartments are evapotranspiration and the various components of streamflow. In the following sections of this chapter the relevance of each compartment in Figure 6 is discussed and the compartments which have a significant influence on shallow subsurface flow are modeled.

Interception and Depression Storage

Interception and depression storage vary with surface conditions, plant growth, wind velocity, rainfall intensity, number of precipitation events and drop size have been estimated to account for 2 to 6 percent of the total precipitation in the Coastal Plain (21). Since interception and depression storage are almost impossible to measure accurately and are not believed to have a significant influence on the shallow subsurface flow process they are not included in the model.

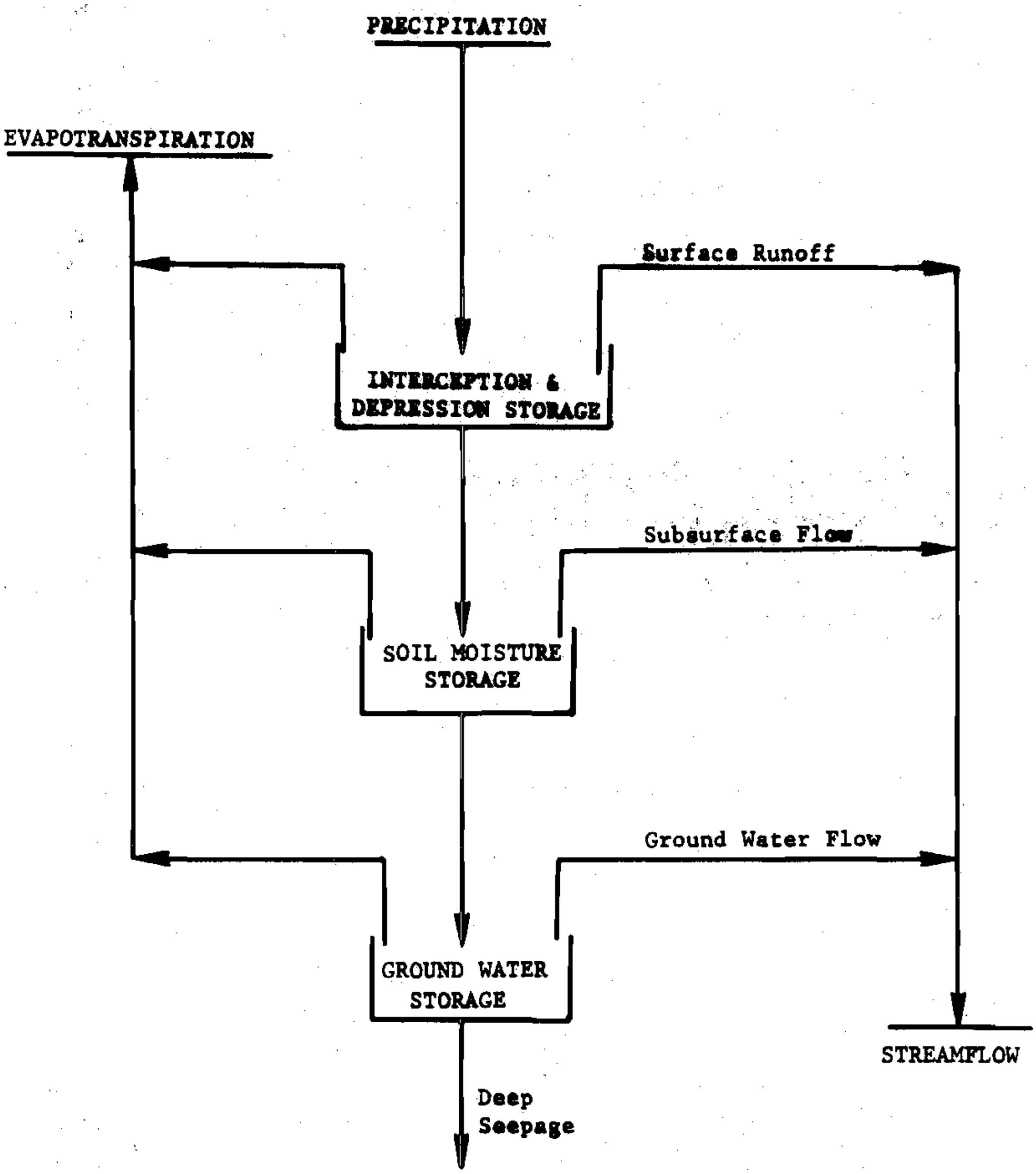

Figure 6. Schematic of the Hydrologic Cycle

Surface Runoff

Since surface runoff was measured separately from shallow subsurface flow at Station Z watershed, it was not necessary to model it. Also, the errors introduced by modeling surface runoff would directly affect the modeling of shallow subsurface flow. To obtain an estimate of the amount of water that infiltrated into the soil, the surface runoff was subtracted from the precipitaiton during the hour in which it occurred. The error caused by subtracting the surface runoff from the precipitation during the hour in which it occurred was insignificant since the average duration of surface runoff events was less than one hour (See Chapter III for more details).

Ground Water Storage and Deep Seepage

On the basis of low permeability of the clay layer it was concluded that seepage losses through the clay layer are negligible (Table 4). Also, contributions from the ground water table to streamflow in the Little River Watershed are negligible because ground water tables in the area are located at least 20 feet below the stream channels (4). Since the ground water and deep seepage components are not important contributors to streamflow in the Little River Watershed, they are not included in the model.

Soil Moisture Storage

The soil moisture storage compartment is the most important part of the subsurface flow model because it directly affects evapotranspiration and shallow subsurface flow. This compartment needs to be divided into a number of vertical and horizontal zones which will accurately describe the distribution of soil moisutre on the watershed. The soil profile description (Table 3) and the moisture holding characteristics of the soil (Table 4) indicate that the soil profile should be divided into three vertical zones. Accordingly, the top zone would be the 0- to 12-in. depth which also corresponds to the average rooting depth of corn. The next zone would be the 12- to 36-in. depth. The 36 in. depth corresponds to the average depth of the clay layer. The third layer would be greater than the 36 in. depth. To further support this zoning, a correlation analysis on the soil moisture data from each tube was performed to determine if the vertical zoning according to moisture characteristics is the same as the above physical zoning.

Also, to determine if shallow subsurface flow affects the zoning, the soil moisture data was divided into subsets. One subset included 66 measurements at each depth which were taken when subsurface flow was recorded at the weir, and the other subset included the remaining 84 measurements taken at each depth when there was no subsurface flow being recorded at the weir. Soil moisutre used in the analysis were the soil moisture taken at the 6, 12, 18, 24, 36, 48 and 54 in. depths for the three tubes. The correlation analysis of the soil moisture data at the various depths will indicate which depths reacted in unison and could be grouped together. The correlation matrices for the three sets of data for each tube are given in Tables 7, 8, and 9. The correlation matrices do not clearly verify the proposed zoning. For example, high correlations between consecutive depths indicate that the soil moisture in the two depths reacted in unison and therefore, could be grouped. On the other hand, non-consecutive depths with high correlation coefficients should not be grouped because they are not physically connected, and such a grouping would be meaningless in the context of zoning the soil profile. To illustrate the vertical zoning of the soil profile according to the correlation coefficients, the groupings of three or more consecutive correlation coefficients having a value greater than 0.60 [significant at the one percent level], are distinguished in Tables 7, 8 and 9 by being enclosed within solid lines. The problem with these groups is that some soil moisture depths are placed in several groups and it is almost impossible to determine in which group they belong. Also, the relative importance of the groups is not distinguished.

Factor analysis was used to produce a clearer set of groupings. The object of factor analysis is to account for the observed intercorrelations among a number of variables with fewer common factors which will better explain the underlying relations and influences. A summary of the significant groupings resulting from factor analysis is given in Table 10. The first three factor groups account for at least 90 percent of the total variance of each data set. The groupings shown in Table 10 are not the same for all tubes and

Table 7. Correlation Matrices for Z1 Soil Moisture Measurements

Total Sample — Sample Size 150

Depth (in)	6	12	18	24	36	48	54
6	1.000						
12	.477	1.000					
18	-.015	.650	1.000				
24	-.030	.142	.756	1.000			
36	.185	.584	.859	.805	1.000		
48	.117	.347	.539	.540	.626	1.000	
54	.124	.512	.780	.722	.875	.612	1.000

No Subsurface Flow Sample — Sample Size 84

Depth (in)	6	12	18	24	36	48	54
6	1.000						
12	.704	1.000					
18	.578	.300	1.000				
24	.145	-.375	.742	1.000			
36	.337	.124	.835	.754	1.000		
48	.121	.038	.283	.262	.334	1.000	
54	.343	.131	.764	.685	.874	.270	1.000

Subsurface Flow Sample — Sample Size 66

Depth (in)	6	12	18	24	36	48	54	Flow
6	1.000							
12	.910	1.000						
18	.794	.832	1.000					
24	-.461	-.552	-.092	1.000				
36	.551	.617	.625	-.093	1.000			
48	-.331	-.396	-.056	.687	-.063	1.000		
54	.210	.150	.206	-.101	.123	.220	1.000	
Flow	.338	.366	.544	.311	.832	.150	-.122	1.000

Table 8. Correlation Matrices for Z2 Soil Moisture Measurements

Total Sample						Sample Size 150	
Depth (in)	6	12	18	24	36	48	54
6	1.000						
12	.566	1.000					
18	.296	.902	1.000				
24	.134	.672	.873	1.000			
36	.210	.616	.790	.937	1.000		
48	-.074	.511	.735	.889	.884	1.000	
54	-.041	.147	.375	.678	.714	.855	1.000

No Subsurface Flow Sample						Sample Size 84	
Depth (in)	6	12	18	24	36	48	54
6	1.000						
12	.884	1.000					
18	.859	.859	1.000				
24	.446	.272	.650	1.000			
36	.314	.140	.511	0.898	1.000		
48	.157	-.038	.338	.769	.861	1.000	
54	-.176	.402	-.035	.624	.714	.816	1.000

Subsurface Flow Sample						Sample Size 66		
Depth (in)	6	12	18	24	36	48	54	Flow
6	1.000							
12	.963	1.000						
18	.926	.938	1.000					
24	.508	.544	.511	1.000				
36	.629	.674	.715	.701	1.000			
48	-.373	-.364	-.346	.357	.119	1.000		
54	-.587	-.579	-.654	.036	-.177	.686	1.000	
Flow	.402	.382	.327	.379	.287	-.147	-.320	1.000

Table 9. Correlation Matrices for Z3 Soil Moisture Measurements

Total Sample — Sample Size 150

Depth (in)	6	12	18	24	36	48	54
6	1.000						
12	.459	1.000					
18	.184	.915	1.000				
24	-.157	.634	.868	1.000			
36	-.422	.523	.706	.807	1.000		
48	-.359	.501	.621	.659	.943	1.000	
54	.295	.283	.204	.052	.124	.232	1.000

No Subsurface Flow Sample — Sample Size 84

Depth (in)	6	12	18	24	36	48	54
6	1.000						
12	.853	1.000					
18	.554	.872	1.000				
24	.000	.477	.803	1.000			
36	.185	.425	.654	.739	1.000		
48	.223	.285	.367	.328	.809	1.000	
54	.203	.194	.129	.022	.551	.783	1.000

Subsurface Flow Sample — Sample Size 66

Depth (in)	6	12	18	24	36	48	54	Flow
6	1.000							
12	.873	1.000						
18	.701	.905	1.000					
24	.259	.422	.739	1.000				
36	.205	.355	.641	.863	1.000			
48	.300	.370	.388	.251	.474	1.000		
54	.105	.112	.001	-.210	-.026	.287	1.000	
Flow	.512	.674	.671	.443	.476	.326	.129	1.000

Table 10. Factor Grouping of Soil Moisture Measurements

FACTOR GROUP[1/]	CONDITIONS: No Subsurface Flow (Sample size = 84)			Subsurface Flow (Sample size = 66)			Total Sample (Sample size = 150)		
	TUBES								
	Z1	Z2	Z3	Z1	Z2	Z3	Z1	Z2	Z3
1	12-36[2/]	18-54	0-12	0-18	0-18	0-18	12-36	18-54	12-24
2	0-6	0-18	36-54	18-24	18-24	18-36	0-6	0-6	0-6
3	36-48		12-36	48-54	24-36	48-54	6-12	6-18	48-54
4				24-36	36-48	36-48	36-48		24-48
5									

1/ Factor groupings in order of significance

2/ Soil moisture zones according to soil moisture readings.

data sets; however, in general, they do indicate that the soil moisture data does support the proposed zoning and that flow conditions do not affect the zoning.

Detailed soil texture mapping of Station Z watershed indicate that the watershed should be divided into two horizontal zones (even through the watershed is classified as one soil type), one zone representing the lower two thirds of the watershed and the other zone representing the upper third of the watershed. A correlation analysis of the soil moisture data was performed to determine if the horizontal zoning of watershed according to moisture characteristics is the same. The soil moisture data used in this analysis were soil moisture data from the three tubes (Z1, Z2, and Z3), with a separate analysis being performed on each depth reading. The correlation matrices for each depth are given in Table 11 and indicate that to a depth of 36 in., the soil moisture data from tubes Z1 and Z2 are highly correlated and could be grouped together. Classifying soil moisture data from tubes Z1 and Z2 into one group, and Z3 into a separate group was supported by laboratory hydraulic conductivity tests which indicate that the upper end of the watershed exhibits faster drainage rates than the lower end (Table 4). A high correlation coefficient for the 48 inch depth for the tubes Z2 and Z3 indicate that the clay layer might need to be zoned differently from the upper soil profile. The total clay layer (54 inch depth) did not substantiate this; therefore a different zoning for the clay layer was not used. In conclusion, the analysis of the horizontal distribution of soil moisture indicated that Station

Table 11. Intertube Correlation Matrices for Tubes Z1, Z2, and Z3

6 1/	Z1	Z2	Z3
Z1	1.00		
Z2	.93	1.00	
Z3	.77	.67	1.00

12	Z1	Z2	Z3
Z1	1.00		
Z2	.96	1.00	
Z3	.63	.68	1.00

18	Z1	Z2	Z3
Z1	1.00		
Z2	.91	1.00	
Z3	.68	.77	1.00

24	Z1	Z2	Z3
Z1	1.00		
Z2	.82	1.00	
Z3	.21	.62	1.00

36	Z1	Z2	Z3
Z1	1.00		
Z2	.95	1.00	
Z3	.79	.77	1.00

48	Z1	Z2	Z3
Z1	1.00		
Z2	.57	1.00	
Z3	.53	.91	1.00

54	Z1	Z2	Z3
Z1	1.00		
Z2	.78	1.00	
Z3	.20	.23	1.00

1/ Indicates depth of reading

2/ Sample size 150

Z watershed should be divided into two horizontal zones. The first zone would encompass the area represented by tubes Z1 and Z2 (lower two-thirds of the watershed) and the second zone would encompass the area represented by tube Z3 (upper third of the watershed).

Since a saturated layer must develop for significant lateral flow to occur in sandy cultivated soils on flat slopes (Figure 7) the well data at Station Z was used to determine if both vertical zones would contain a horizontal flow component. The well data indicated that the water table had never risen closer than 1 foot of the surface; therefore, the 12- to 36-in. zone can be reasonably assummed to contain the horizontal flow component. To further support this conclusion a regression analysis relating soil moisture to shallow subsurface flow was performed. A total of 64 observations were used in this analysis which included those soil moisture values taken when subsurface flow was occurring. First, the soil moisture in the 12- to 36-in. zone was linearly related to the subsurface flow rate, and then the soil moisture in the 12- to 36-in. zone and the 0- to 12-in. zone were related to the subsurface flow rate.

$$Q = 0.0155 + 0.0024*S_{12-36} \tag{3}$$

Correlation coefficient = 0.92

Standard error of estimate = 0.0014 in.

and

$$Q = 0.0134 + 0.0002*S_{0-12} + 0.0020*S_{12-36} \tag{4}$$

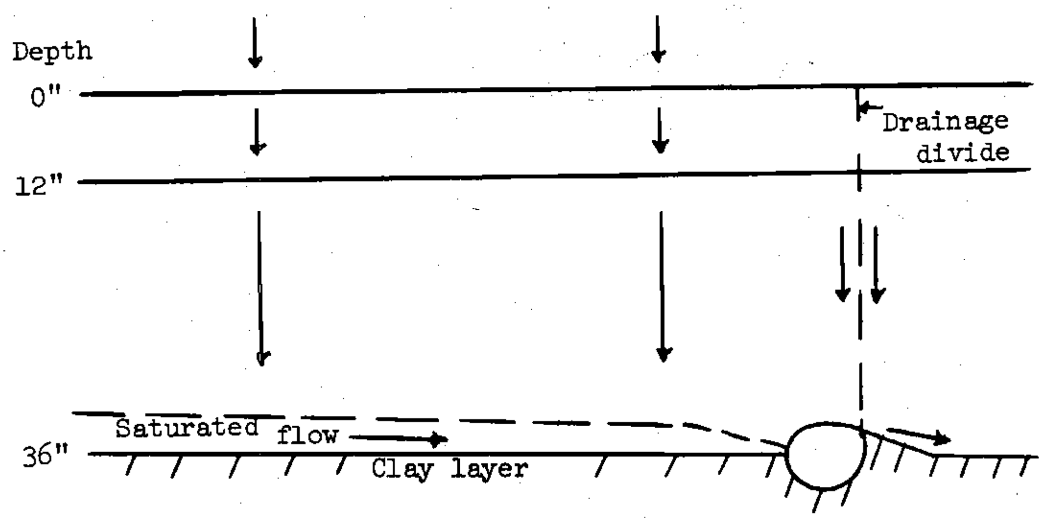

Figure 7. Flow Schematic

Correlation coefficient = 0.92

Standard error of estimate = 0.0014 in.

where

Q = subsurface flow (in/hr)

S_{o-12} = soil moisture in the 0- to 12 in. zone (in)

S_{12-36} = soil moisture in the 12- to 36 in. zone (in)

The correlation coefficients and standard errors of equations 3 and 4 indicate that inclusion of the 0- to 12-in. zone does not significantly increase the accuracy. Also, examination of the coefficients indicates the coefficient of the 0- to 12-in. zone is not significant [1 percent level]; therefore, it was concluded that the predominate flow process in 12- to 36-in. zone is the lateral subsurface flow component, while the predominate flow component in the 0- to 12-in. zone is the vertical flow component.

The determination of the maximum water-holding capacity and the capacity when horizontal and vertical flow will begin is critical to the subsurface flow model. The maximum water-holding capacity was initially determined by laboratory analysis of soil samples taken at each end of the watershed. These capacities are summarized for the 0- to 12-in. and 12- to 36-in. zones in Table 4. However, a maximum water-holding capacity of the soil is seldom reached because of air entrapment and nonconnected pores. Therefore, the soil moisture data collected from the infiltration plots located on Station Z and the long-term soil moisture data collected at Station Z were examined to determine the maximum water-holding capacity under field conditions.

The soil moisture data from the infiltration plots indicate that after 10 inches of water were applied to each plot only 85 percent of the voids in the top 36 inches of soil were filled (Appendix A). Also, the maximum soil moisture [Table 12] for the period (October 1968 to October 1971) at Station Z indicated a maximum of 80 percent of the voids were filled. Using this information, the maximum water-holding capacity under field conditions was set at 85 percent of total porosity. These capacities are summarized for the four vertical zones in Table 4.

The soil moisture capacity, when horizontal and vertical drainage begins or ends, was not as easily determined as the maximum capacity because it is not directly measurable. Since only the soil moisture values taken at Tube Z1 were responsive to subsurface flow, an analysis to determine the soil moisture content at the beginning and end of subsurface flow was performed only on Tube Z1. The soil moisture at the beginning and end of subsurface flow was not consistent for the 0- to 12-in. zone, but was consistent for the 12- to 36-in. zone. The soil moisture at the start of subsurface flow for the 12- to 36-in. zone averaged 6.58 inches, and the soil moisture at the end of the subsurface flow averaged 6.50 inches. Therefore, it was concluded subsurface flow begins and ends at a water-holding capacity of 6.55 inches for the 12- to 36-in. zone at the lower end of the watershed. When this result was related to tension by using the moisture-tension data given in Table 4, it was found to be the amount of moisture held at 0.1 bar tension. Using the ratio of the moisture held at 0.1 bar tension to the maximum water-holding capacity given in Table 4, and

Table 12. Statistical Soil Moisture Analysis

Flow Conditions	Sample Size	Tube	Depth (in)	Soil Moisture Mean (in)	Soil Moisture Standard Deviation (in)	Range Min. (in)	Range Max. (in)
Subsurface flow and no subsurface flow	150	Z1	0-12	1.78	0.43	0.74	2.52
	150	Z1	12-26	6.37	0.38	5.10	7.15
	150	Z2	0-12	1.93	0.45	0.90	2.69
	150	Z2	12-36	6.88	0.35	5.91	7.40
	150	Z3	0-12	1.02	0.34	0.14	2.01
	150	Z3	12-36	5.55	0.50	4.40	6.40
No subsurface flow	84	Z1	0-12	1.61	0.41	0.74	2.44
	84	Z1	12-36	6.18	0.39	5.10	6.67
	84	Z2	0-12	1.75	0.43	0.90	2.66
	84	Z2	12-36	6.71	0.36	5.91	7.25
	84	Z3	0-12	0.85	0.33	0.14	1.43
	84	Z3	12-36	5.31	0.47	4.40	6.14
Subsurface flow	66	Z1	0-12	1.99	0.36	1.01	2.52
	66	Z1	12-36	6.61	0.13	6.27	7.15
	66	Z2	0-12	2.16	0.36	1.08	2.69
	66	Z2	12-36	7.11	0.16	6.79	7.40
	66	Z3	0-12	1.23	0.22	0.77	2.01
	66	Z3	12-36	5.86	0.33	5.03	6.40

the maximum water-holding capacity of the upper end of the watershed, it was determined that horizontal flow from the upper area would begin at a storage of 5.50 inches of water. Since it was impossible to determine from the soil-moisture data when vertical drainage from the 0- to 12-inch zone would begin or end, the water-holding capacity held at 0.33 bar tension was assumed since this value has previously been established as a reasonable value (21). Thus, the water-holding capacity at which vertical drainage begins for the 0- to 12-in. zone equals 1.60 inches for the lower area and 1.25 inches for the upper area.

In conclusion, the soil-moisture storage compartment for Station Z watershed was divided into 2 vertical zones and 2 horizontal zones. The vertical zones were the 0- to 12-in. depth and the 12- to 36-in. depth. The horizontal zones were the upper third of the watershed and the lower two-thirds of the watershed. The 0- to 12-in. zone primarily contributed only vertical flow while the 12- to 36-in. zone primarily contributed only horizontal flow.

Evapotranspiration

Evapotranspiration is one of the most significant hydrologic processes accounting for approximately 63 percent of the precipitation (see Chapter III). Since the soil moisture compartment was divided into two vertical zones, the evapotranspiration function needs to be capable of withdrawing moisture from both zones simultaneously. Evapotranspiration was modeled by a decay-type function relating soil moisture at any time to some initial soil moisture. This type of relation has been used successfully by other authors (27,39) and is expressed by the equation:

$$ET_t = SM_o - SM_o K_D^t \tag{5}$$

where,

ET_t = estimated evapotranspiration from the top D in. of soil for t days since the last observation (in)

t = number of days since last observation

SM_o = soil moisture in the top D in. of soil at last observation (in)

K_D = ratio of the soil moisture on any day to the previous days' soil moisture for the top D in of soil (to be referred to as depletion constant)

D = depth of soil measured from surface (in)

The $SM_o * K_D^t$ factor in equation 5 is the soil moisture in the top D in. of soil t days since the last observation.

In order to determine evapotranspiration from equation 5 values for the depletion constant, K_D, are needed. The variables used to describe the depletion constant, K_D, are available soil moisture in the top D in. of soil, SM_o, average pan evaporation for the time period, PE, and growth index for the crop, GI. A data base of K_D's for various depths D was determined from equation 5 (Appendix D) using the Station Z water balance data (Chapter III) when no significant vertical and horizontal drainage was occurring (soil moisture less than that held at 0.3 bar tension). Even though the extremely wet conditions were not included in this analysis, the K_D's will not be significantly different because evapotranspiration is constant over the excluded moisture range (39). A linear relationship relating the above variables to the depletion constant was developed for corn at Station Z. The relationship is

$$K_{36} = 0.99162 - 0.01522*GI + 0.00290*PE - 0.00006*SM_o \qquad (6)$$

Correlation coefficient = 0.62

Standard error of estimate = 0.0005

where,

K_{36} = depletion constant

SM_o = initial soil moisture in the top 36 in. of soil (in)

PE = average daily pan evaporation for the period (in)

GI = growth index of crop--a ratio of current evapotranspiration to that at maturity taken from Holtan (21) (Figure 8)

The pan evaporation and soil moisture terms in equation 6 do not make a significant contribution (5 percent level) to the equation and can be eliminated from equation 6; however, they might need to be included in other studies because of their physical significance. Total evapotranspiration for the top 36 in. of soil can be determined by substituting into equation 5 the initial soil moisture SM_o, and K_{36} from equation 6.

In order to describe accurately the distribution of soil moisture within the profile, the evapotranspiration from the top 36 in. needs to be distributed with depth. To solve this problem a continuous function relating the depletion constant, K_D, to depth was developed to distribute the evapotranspiration predicted for the top 36 in. of soil. Graphs of the depletion constant versus depth

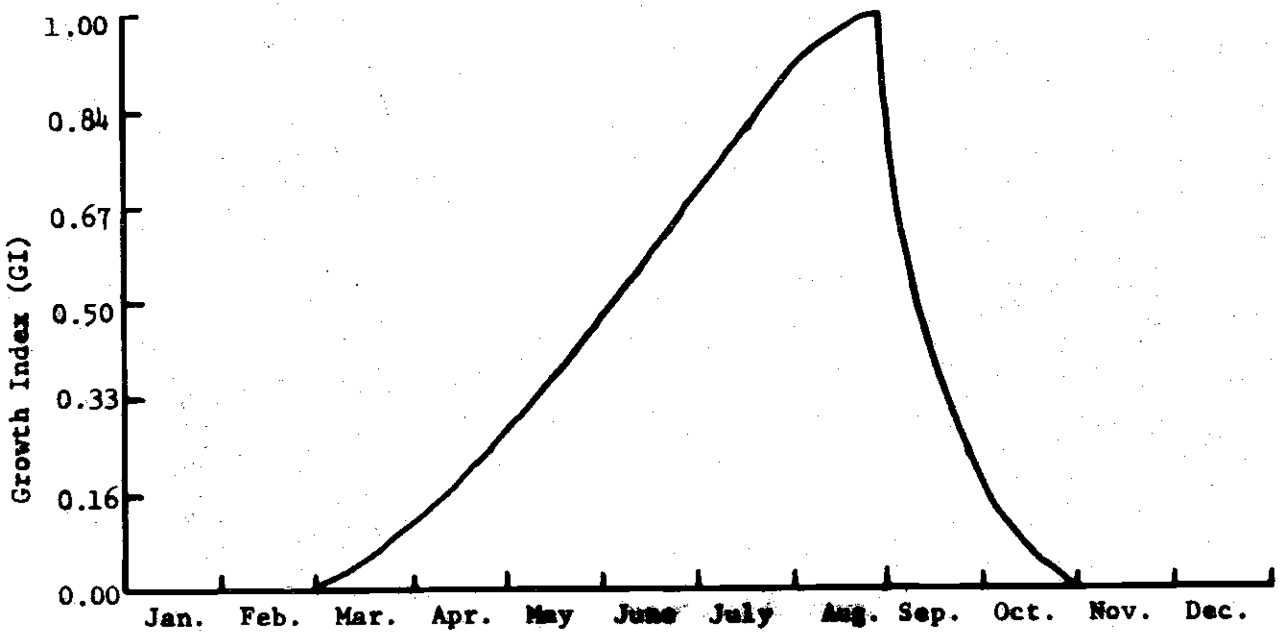

Figure 8. Distribution of Growth Index for Corn (21)

(Appendix D) indicated a semilogarimetric relationship of the form

$$K_D = a + b*Loge(D) \tag{7}$$

where,

K_D = depletion constant

D = depth of soil measured from surface (in)

a = shift coefficient

b = shape coefficient

When equation 7 was fitted by the least squares technique to the data base of K_D's for various depths D generated from equation 5 using Station Z water balance data (Chapter III and Appendix D) when no significant vertical and horizontal drainage was occurring (soil moisture less than that held at 0.3 bar tension), it was found that the shape coefficient, b, essentially remained constant. Therefore, it was assumed that the shift coefficient, a, would vary to account for changing evapotranspiration rates. Substituting the shape coefficient into equation 7 yields

$$K_D = a + 0.019*Loge(D) \tag{8}$$

Average correlation coefficient = 0.91

Average standard error of estimate = 0.0002

where,

K_D = depletion constant

D = depth of soil measured from surface (in)

a = shift coefficient

The shift coefficient for a given location can be determined from equation 8 by substituting the depletion constant, K_D, determined from equation 6 for a depth of 36 inches. Once the shift coefficient, a, is determined, equation 8 can be used to determine K_D for any value of D. Substituting the various K_D's along with the corresponding initial soil moisture, SM_o, into equation 5, the total evapotranspiration for various surface to depth D soil zones can be determined. Substracting sequential evapotranspiration values the evapotranspiration for intervening layers, such as the 12- to 36-in. layer, can be determined (Figure 9).

In summary, the procedure to estimate and distribute evapotranspiration with depth is to

[1] solve equation 6 for a depletion constant, K_{36}, for the top 36 in. of soil;

[2] solve equation 8 for the shift coefficient, a; using the depletion constant, K_{36}, determined in Step 1 and a D of 36 in.

[3] solve equation 8 for K_{12}

[4] predict evapotranspiration from equation 5 for the 0- to 12-in. and 0- to 36-in. soil zones using the initial soil moisture profile, and the depletion constants derived in Step 1 and 3 (ex.: Figure 9, ET_{o-12}, ET_{o-36}) and

[5] distribute the evapotranspiration with depth by subtracting sequential evapotranspiration values obtained in Step 4 (ex.: Figure 9, $ET_{12-36} = ET_{o-36} - ET_{o-12}$).

The above procedure predicts daily evapotranspiration. The aliquots given in Figure 10 (37) were used to distribute the daily total into hourly amounts. The change in the shape of the hourly distri-

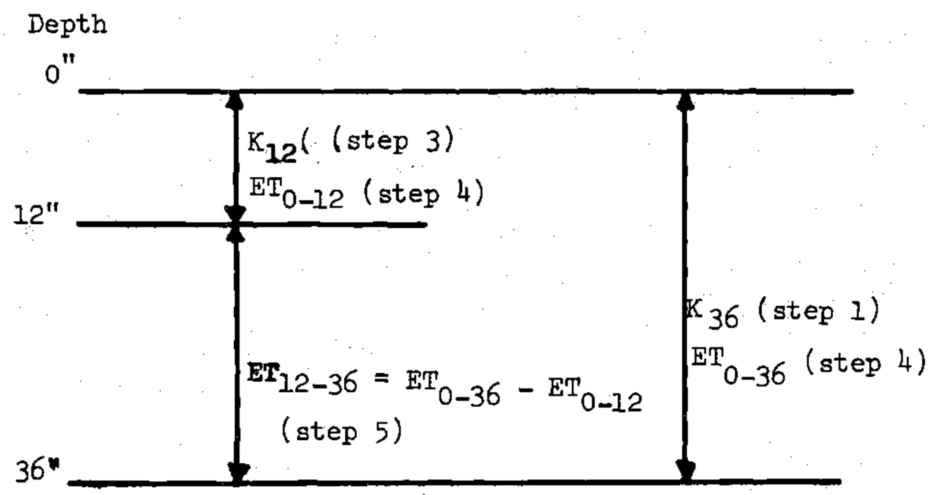

Figure 9. Example Evapotranspiration Computation

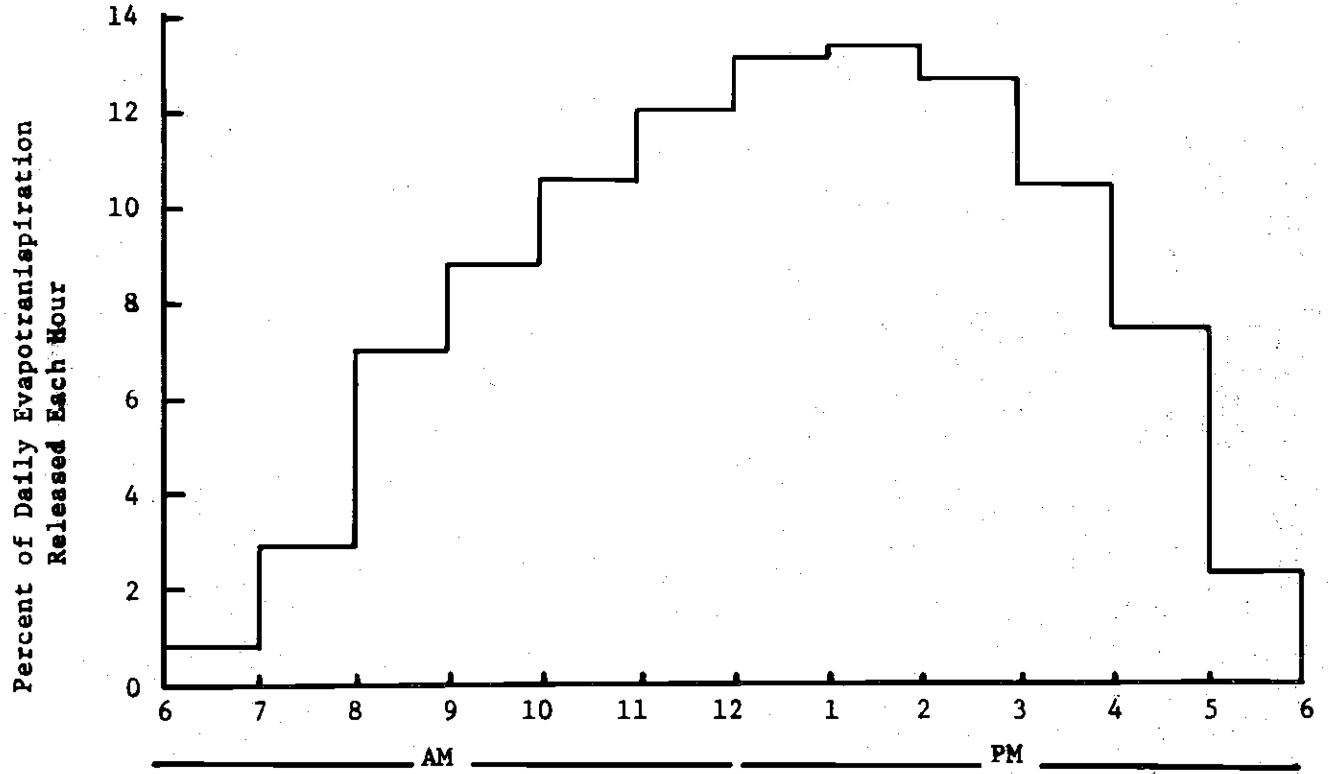

Figure 10. Hourly Distribution of Evapotranspiration

bution of evapotranspiration from day to day was not significant; therefore, the distribution shown in Figure 10 was used at all times.

In conclusion a method for determining evapotranspiration from both vertical soil moisture zones has been developed.

Subsurface Flow

Two distinct types of subsurface flow peaks were observed at Station Z watershed. The first type occurred with no antecedent flow, and the second type occurred with antecedent flow. Table 13 summarizes the flow and timing characteristics of both types of peaks. The peaks with antecedent flow rise faster than the peaks without antecedent flow. All hydrographs exhibit a long recession and a typical example is illustrated in Figure 11. The recessions were usually linear with a rate of change ranging between 0.12 inches per day to 0.40 inches per day with an average rate of change for all events of 0.23 inches per day. The recession rate varied seasonally, with the winter and spring months exhibiting the faster rates. Thus, in order to model these types of flow characteristics, a function relating subsurface flow to storage was sought to produce hydrographs with a sharp rising limb, flat peaks, and a long recession.

Several types of storage functions were investigated which can produce the shape of the hydrograph shown in Figure 11. The function used was the hyperbolic tangent because the coefficients could be related to the physical characteristics of the soil. The equation used to describe shallow subsurface flow is

Table 13. Summary of Hydrograph Peaks

Peak flow characteristics of the 14 peaks with no antecedent flow

	Mean	Min.	Max.
Peaks (cfs)	0.0089	0.0013	0.0274
Time from start of flow to peak (hrs)	9	3	32
Time from mean of rainfall to peak flow (hrs)	17.0	0	85.0
Time flow stays at ± 3% of peak flow (hrs)	4.14	2	9
Time from mean of rainfall to start of flow (hrs)	4.0	0	13.4

Peak characteristics of 38 peaks with antecedent flow

	Mean	Min.	Max.
Peaks (cfs)	0.0099	0.0004	0.0412
Time from trough to peak flow (hrs)	5	2	13
Time from mean of rainfall to peak flow (hrs)	2.61	0.50	8
Time flow stays at ± 3% of peak flow (hrs)	3.97	1	10

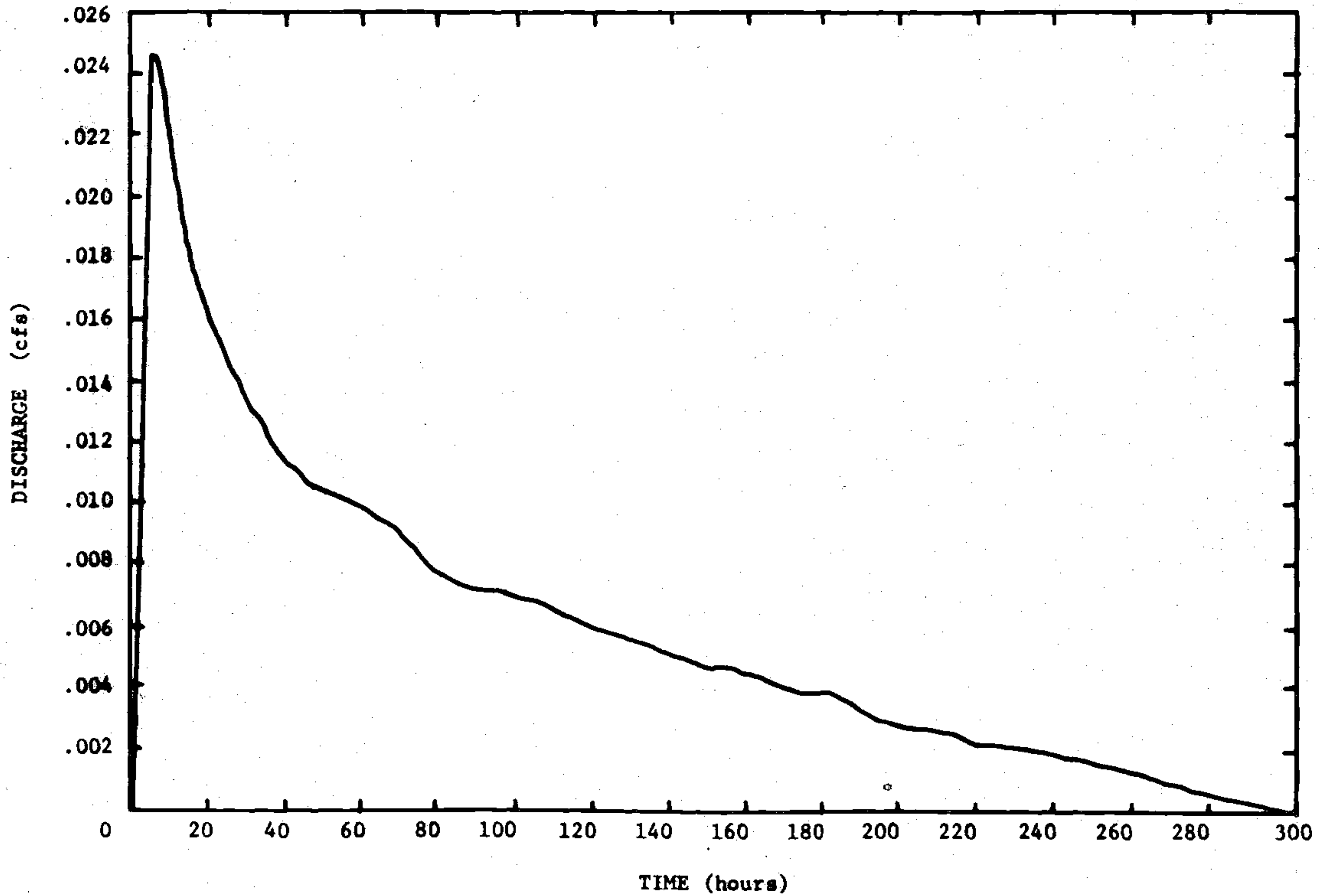

Figure 11. Subsurface Hydrograph for Event of September 21,1969

$$Q_t = (S_t - a*\tanh(b*S_t))/\Delta t = (S_t - a*(\frac{e^{b*S_t} - e^{-b*S_t}}{e^{b*S_t} + e^{-b*S_t}}))/\Delta t \qquad (9)$$

where

Q = subsurface flow (in/hr)

S = soil moisture storage minus the soil moisture storage when drainage begins (in)

a = available storage between the soil-moisture storage when drainage starts and the maximum soil moisture storage under field conditions (in)

b = drainage characteristic of the soil as defined by the hyperbolic tangent (in^{-1})

t = time in hours

tanh = hyperbolic tangent

e = base of Naparian logarithms

Equation 9 is illustrated in Figure 12. The flexibility of equation 9 to produce the general shape of the subsurface flow hydrograph is shown in Figure 13 for a three inch storm occurring during the first hour. Also, as can be seen in Figure 13, the variation of parameters "a" and "b" can produce a variety of shapes; therefore, equation 9 was used to describe both horizontal and vertical drainage. The parameters "a" and "b" in equation 9 represent specific physical properties, thus their values should fall within a range allowed by the physical concept. Since parameter "a" is designed to represent a measurable physical property, it was decided to set "a" and not allow it to enter the calibration process.

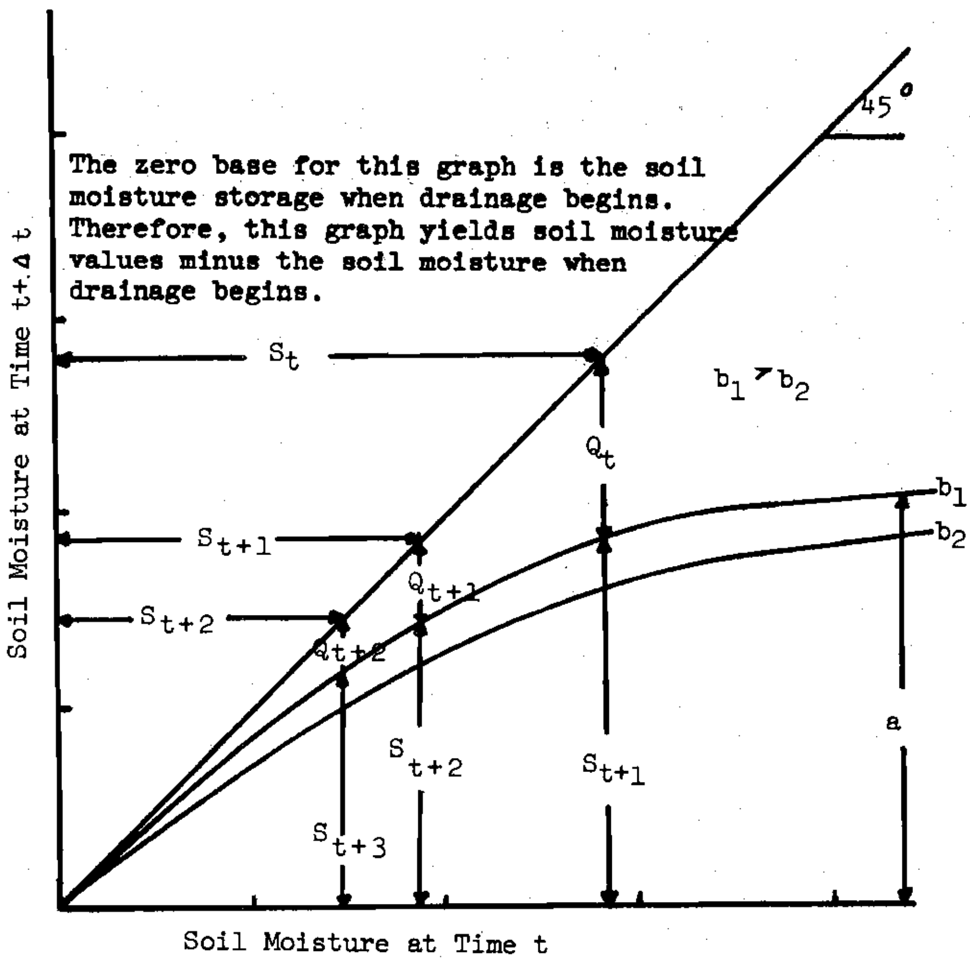

Figure 12. Drainage Function Without Inflow or ET

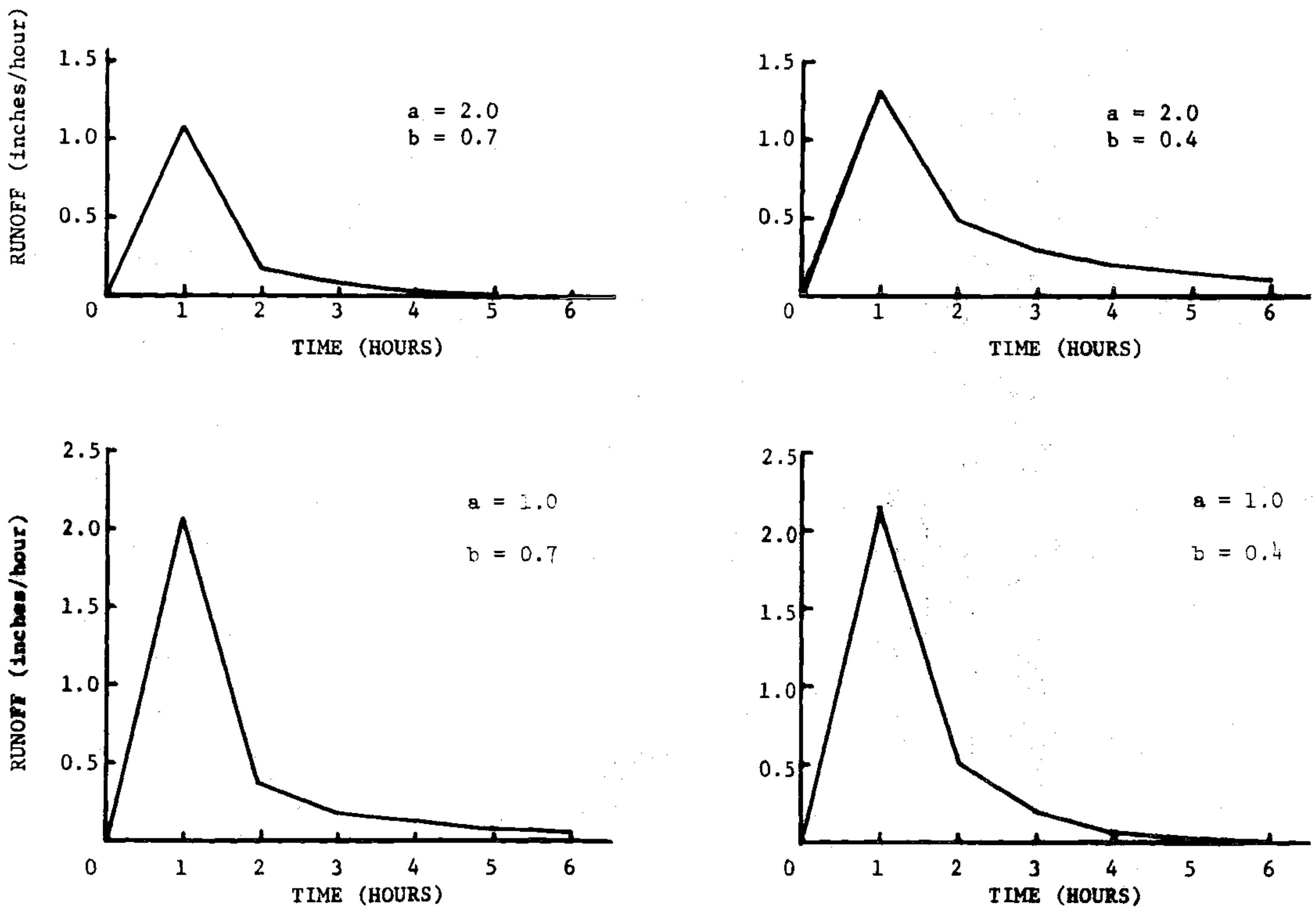

Figure 13. Flexibility of the Hyperbolic Tangent for a 3-inch Storm

Each of the four soil zones summarized at the end of the soil moisture section have a "a" and "b" parameter to be determined. The "a" parameters were determined by substracting the soil moisture when drainage begins from the maximum soil moisture storage under field conditions (Table 4) for each specific zone. With the "a" parameters set at a constant value examination of equation 9 indicated that for certain "b" values the hyperbolic tangent would cross the 45^{o} line (Figure 12); thus producing a negative flow rate. Since negative flow rates are physically impossible, upper limits were placed on "b's" to eliminate this. The upper limits for the four "b's" were determined by setting the slope of the hyperbolic tangent equal to 1 at $S_{\dagger} \cong 0$. The specific value of the "a's" and limits of the "b's" for the four zones are summarized in Figure 14.

A comparison of the maximum flow rates produced by equation 9 using the upper limits and the maximum subsurface flow rates measured at Station Z showed that equation 9 would produce unrealistically high rates. To correct this it was decided to add a scaling coefficient to equation 9. Preliminary investigations indicated that two scaling coefficients instead of one were needed to account for the fact that the rising side of the hydrograph exhibited faster drainage rates than did the recession side. One scaling parameter was applied to the rising side of the hydrograph and one to the recession side. To produce the observed drainage characteristics, the scaling parameter for the rising side of the hydrograph had to be greater than the one for the recession side. Adding the scaling parameters to equation 9 gives

$$Q_t = (c^*(S_t - a^*\tanh(b^*S_t)))/\Delta t \qquad Q_{t-1} \geq Q_{t-2} \tag{10}$$

and

$$Q_t = (d^*(S_t - a^*\tanh(b^*S_t)))/\Delta t \qquad Q_{t-1} \geq Q_{t-2} \tag{11}$$

where

Q = subsurface flow (in/hr)

S = soil moisture storage minus the soil moisture storage when drainage begins (in)

a = available storage between the soil-moisture storage when drainage starts and the maximum soil moisture storage under field conditions (in)

b = drainage characteristic of the soil

t = time in hours

c = scaling parameter for rising side of the hydrograph ($c \leq d$)

d = scaling parameter for recession side of the hydrograph ($d < c$)

tanh = hyperbolic tangent

Summary

In the previous sections the individual components of the subsurface flow model for Station Z watershed were described. The total soil water accounting process can be expressed by

$$Q_t = (S_t - S_{t+1} + I_t - ET_t)/\Delta t \tag{12}$$

where

S = soil moisture storage (in)

Q = subsurface flow (in/hr)

I = inflow into the zone [vertical and or horizontal drainage] (in)

ET = evapotranspiration (in)

t = time (hr)

A summary of these components is shown in Figure 14. Input for the model is

1. Hourly rainfall minus surface runoff
2. Average daily pan evaporation
3. Daily growth index for the crop
4. Initial soil moisture conditions for each zone
5. Soil-moisture storage values at the beginning of drainage for each zone
6. Maximum soil-moisture storage for each zone
7. Values of the drainage characteristic (b) for each zone (methods of estimating these will be presented in the next chapter)

Output from the model is

1. Hourly subsurface flow
2. Hourly evapotranspiration from each zone
3. Hourly percolation from the top zone to the lower zone.
4. Hourly soil moisture storage for each zone.

A fortran listing of the optimization routine and subsurface flow model are given in Apprndix C along with the program input and output for event 1. The process by which the model generates flow is graphically illustrated in Figure 12.

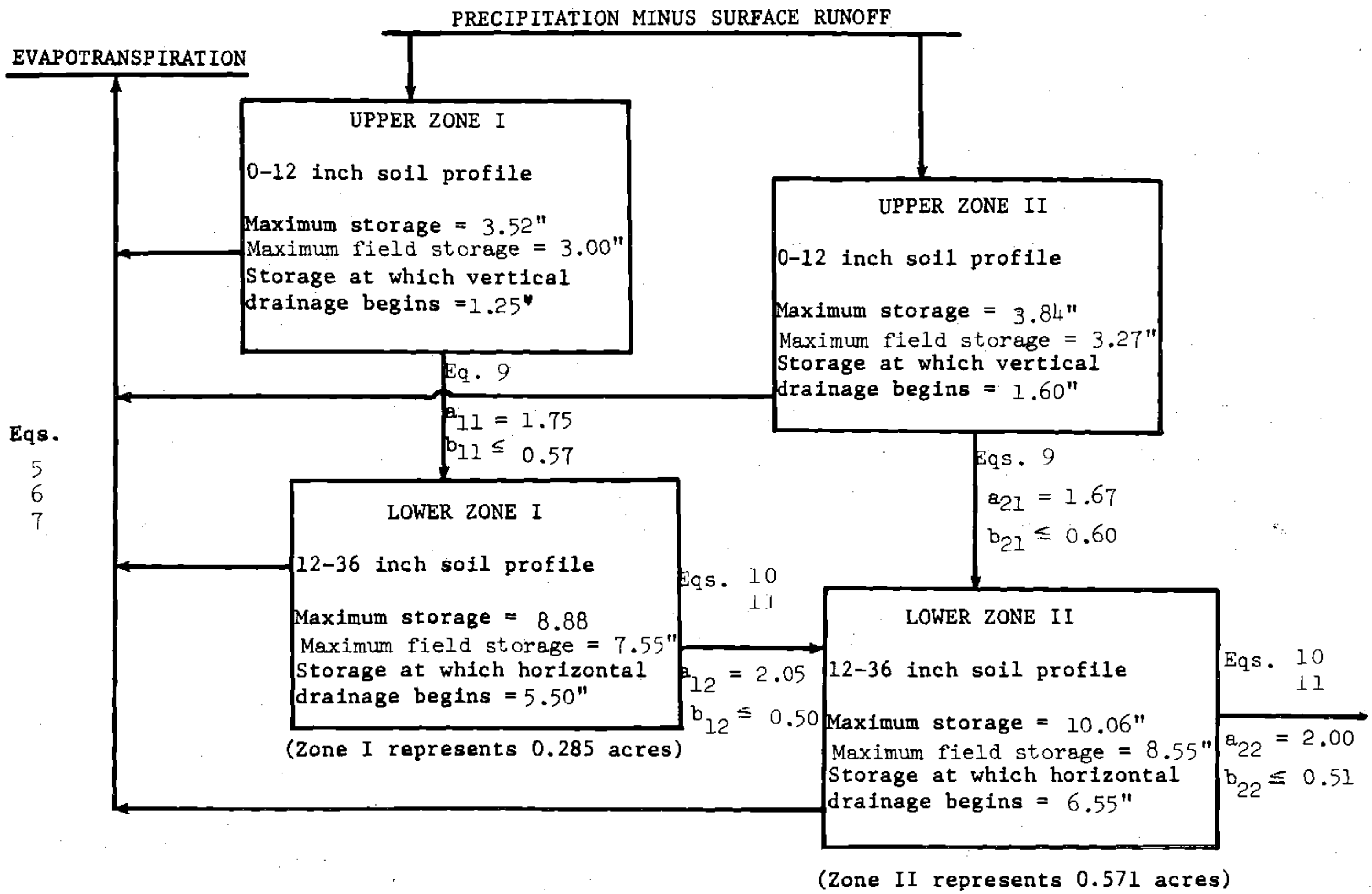

Figure 14. Schematic of Subsurface Flow Model

CHAPTER V

MODEL TESTING

The preceding chapter has described the conceptual development of the shallow subsurface flow model. This chapter is concerned with calibration and verification of that model. The calibration section will cover [1] optimization of the model parameters with a number of measured events, and [2] a sensitivity analysis of the model parameters. The verification section will describe how well the calibrated model can simulate the measured events not used in calibration and how the parameters can be estimated.

For the period October 1968 to October 1971 there were 14 subsurface flow events. These events are summarized in Table 13. Four events were selected for model verification. This limited number of events covers a range of [1] seasons, [2] length of events, [3] types of events (single or multiple peaked events), and [4] maximum flow rates. Events 3, 11, 13, and 14 were chosen for verification. The remaining events were then used for calibration.

Since the model is capable of simulating periods of zero subsurface flow, the duration of the events for calibration and verification were extended to begin with the set of soil moisture measurements immediately before subsurface flow began and to end the day subsurface flow ended. This extension minimizes errors introduced by estimating the initial soil moisture conditions. On the IBM 360-75 computer the average optimized event took approximately 20 seconds of which 18 seconds was used for optimization

Calibration

The pattern-search-optimization technique as modified by TVA was used to determine the parameter values for the model (15). This technique was used because [1] the model could be entered as a subroutine without reprogramming the optimization portion of the program; [2] limits could be placed on the parameters; [3] the sensitivity of each parameter could be determined; and [4] four criteria for optimization were available. A Fortran listing of the optimization routine and the subsurface flow model are given in Appendix C. For this study the optimization criterion function used was minimization of the sum of squares of errors between the observed and predicted hourly flow rates.

A visual comparison of the observed and predicted hydrographs is a method of evaluating the accuracy of the model, however, it is almost completely subjective. For objectively comparing the closeness of fit, the correlation coefficient and the percent standard error of estimation were computed for the observed versus predicted hourly flow rates. The percent standard error of estimation was computed by first dividing the value of the objective function (the sum of squares of the difference between the observed and predicted hourly subsurface flow rates) for each optimized event by the difference between the number of data points and the number of parameters optimized, and then taking the square root. This result was then divided by the average runoff rate for each event and multiplied by 100 to express the result in percent. This percent standard error of estimation provides a convenient measure of comparison. Also three summaries were made to allow some additional objective interpretation. The first summary was a comparison of the observed and predicted peak subsurface flow rates and the time those peaks occurred. The second summary compares the observed and predicted event volume of subsurface flow, and the last summary is a comparison of the observed and predicted soil moisture in the four zones. Since the optimization only involved the fitting of the hydrographs, the soil moisture comparison is a validation of the moisture accounting portion of the model.

The optimized parameters for the 10 events are shown in Table 14 along with the respective correlation coefficient and the average percent error of estimation. The predicted and observed hydrographs are shown in Figures 15 through 24. The model did reasonably well in predicting all events except events 1 and 8. Close examination of events 1 and 8 indicated that they were extremely small events and did not exhibit the typical subsurface flow hydrograph shape. Because of the extremely small flow in events 1 and 8, it is possible that the collection system and measuring device might introduce large errors which would cause the measured hydrographs to be unrepresentative, thus the results of these two events were not included in the following discussion.

For the eight events, the model produced an average correlation coefficient of 0.89 and an average standard error of estimation of 43 percent. Comparison of the observed and predicted peak rates are

Table 14. Optimized Parameters for the Subsurface Flow Model

Event No.	Optimized Parameters[1]						Correlation Coefficient	Percent Std. Error of Estimation
	b_{11}	b_{12}	b_{21}	b_{22}	c	d		
1	0.57	0.50	0.60	0.51	0.006	0.003	0.75	147
2	0.57	0.50	0.60	0.51	0.056	0.040	0.98	24
4	0.57	0.41	0.59	0.44	0.034	0.017	0.91	44
5	0.57	0.50	0.60	0.50	0.092	0.068	0.94	30
6	0.57	0.50	0.60	0.48	0.035	0.020	0.74	57
7	0.57	0.50	0.60	0.44	0.043	0.024	0.95	44
8	0.57	0.50	0.60	0.51	0.026	0.010	0.74	72
9	0.57	0.50	0.60	0.48	0.093	0.034	0.85	56
10	0.48	0.40	0.56	0.51	0.032	0.031	0.87	56
12	0.56	0.40	0.57	0.40	0.054	0.030	0.87	34
Average[2]	0.56	0.46	0.59	0.47	0.055	0.033	0.89	43

[1]First Subscript refers to sub area and second subscript refers to soil zone (ex: b_{11} upper area and upper zone).

[2]Events 1 and 8 excluded

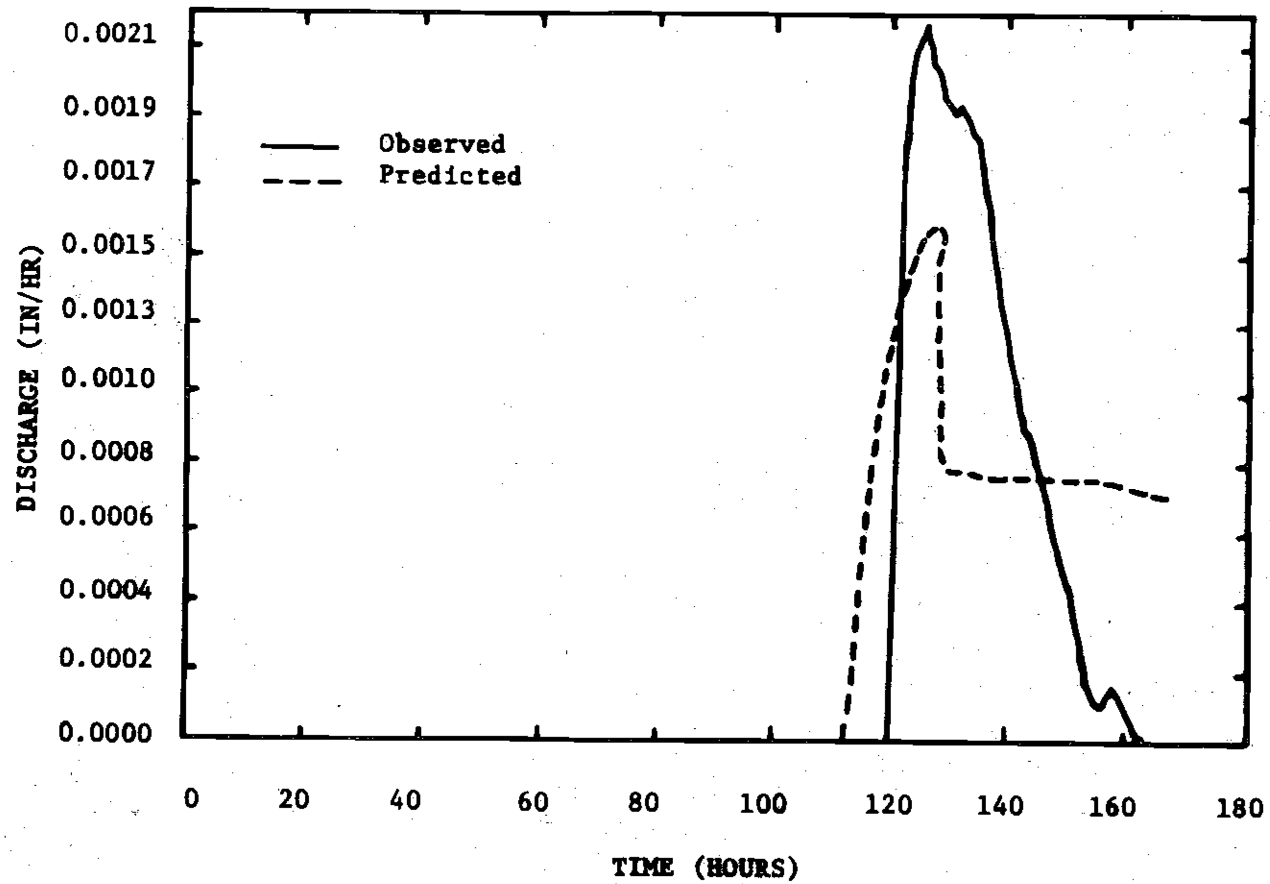

Figure 15. Subsurface Flow Event 1, November 29,1968 to December 6, 1969

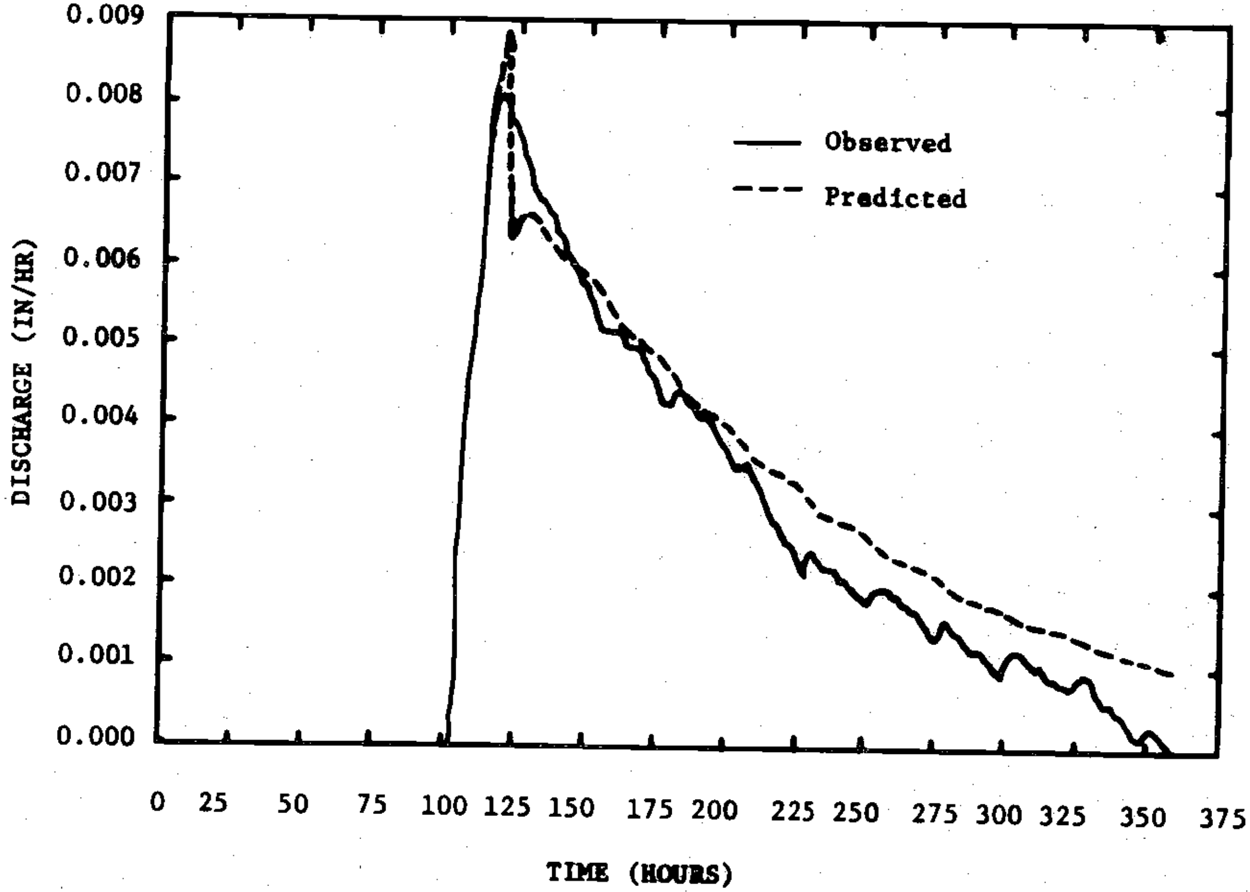

Figure 16. Subsurface Flow Event 2, December 27, 1968 to January 10, 1969

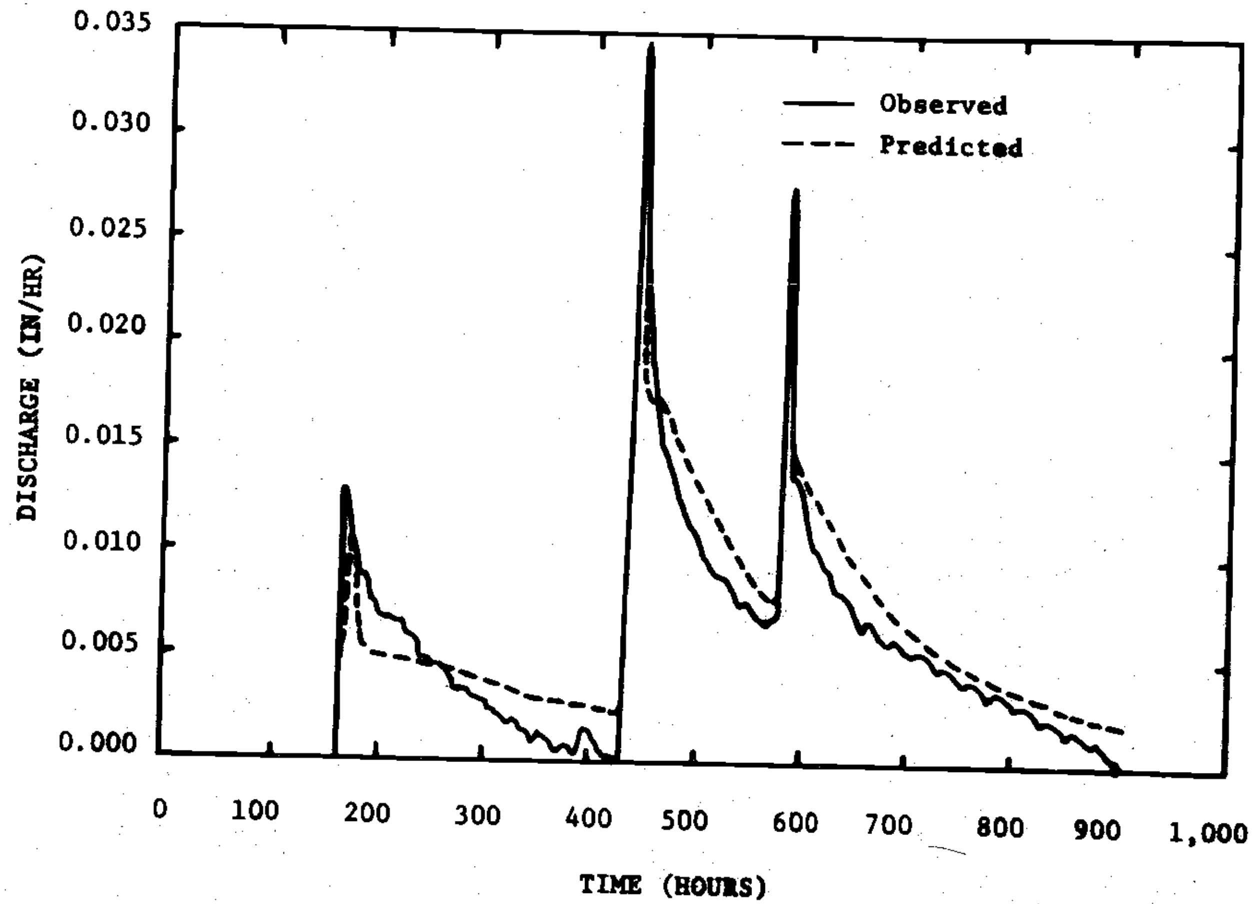

Figure 17. Subsurface Flow Event 4, February 28, 1969 to April 6, 1969

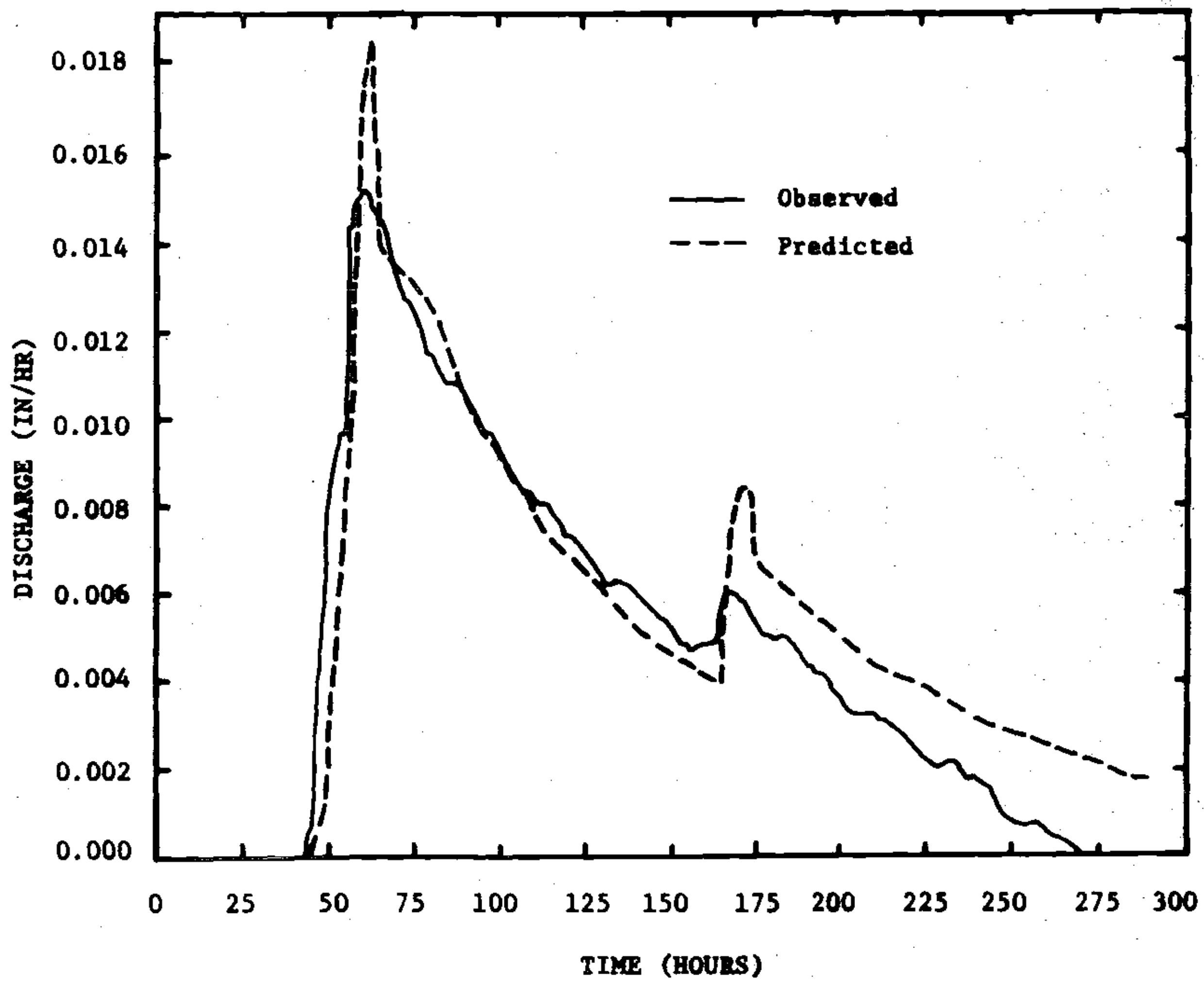

Figure 18. Subsurface Flow Event 5, May 17, 1969 to May 29, 1969

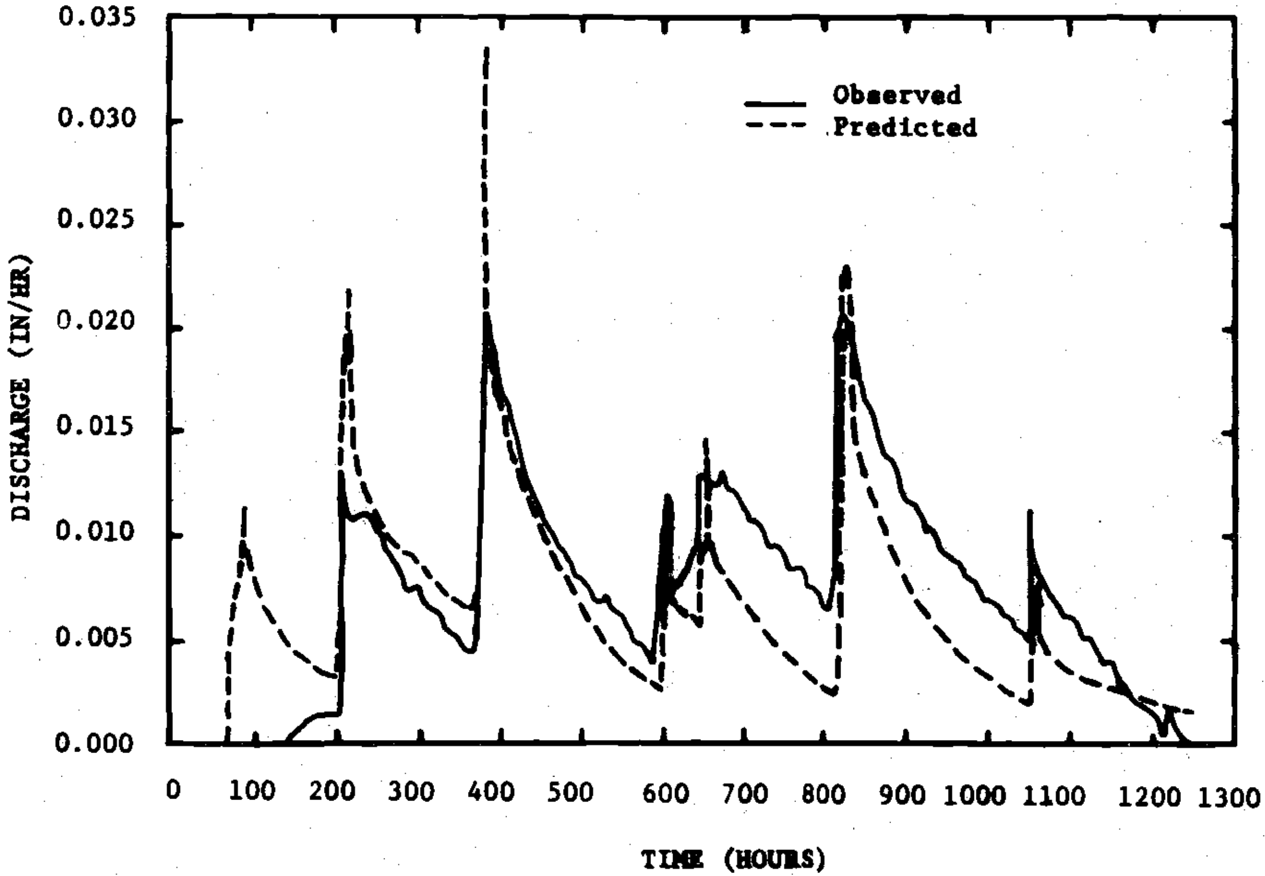

Figure 19. Subsurface Flow Event 6, July 25, 1969 to September 9, 1969

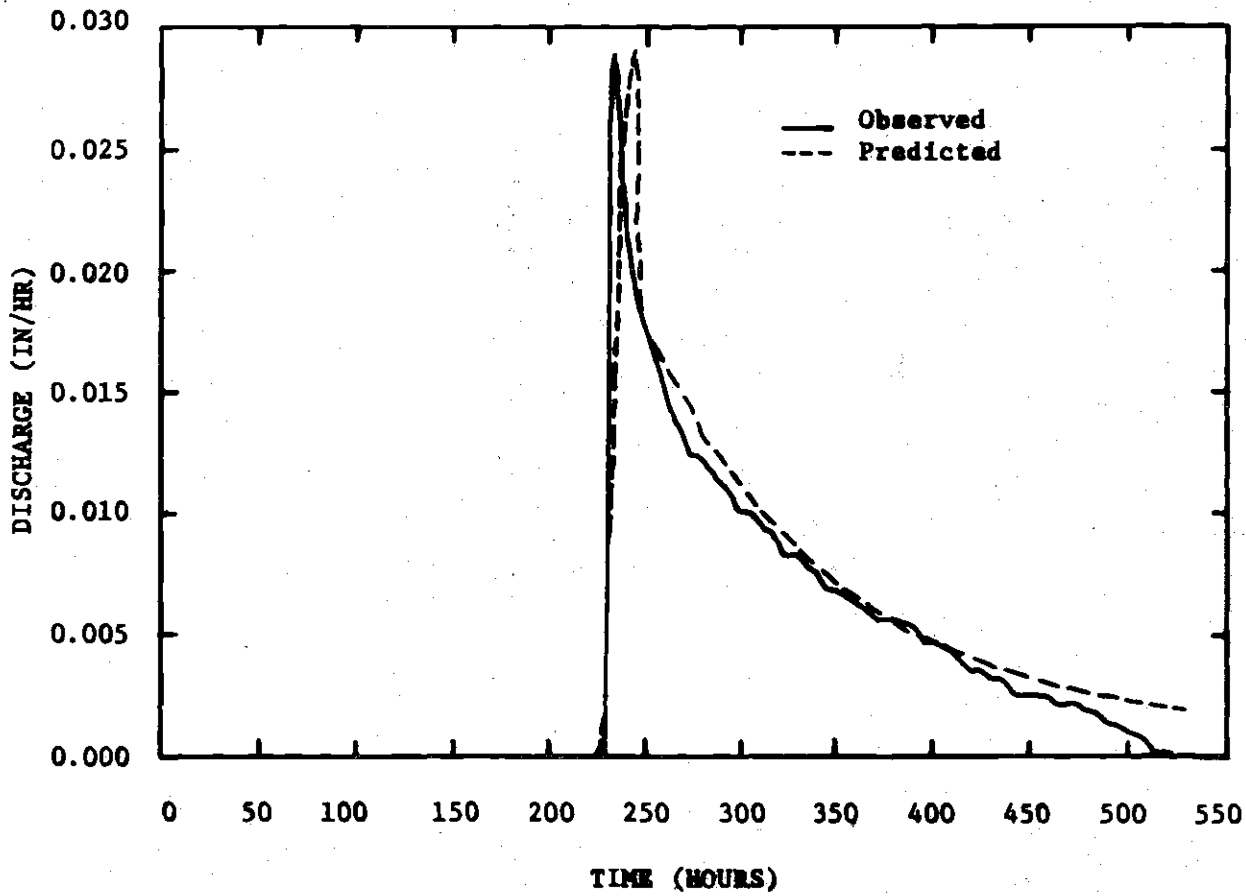

Figure 20. Subsurface Flow Event 7, September 12, 1969 to October 3, 1969

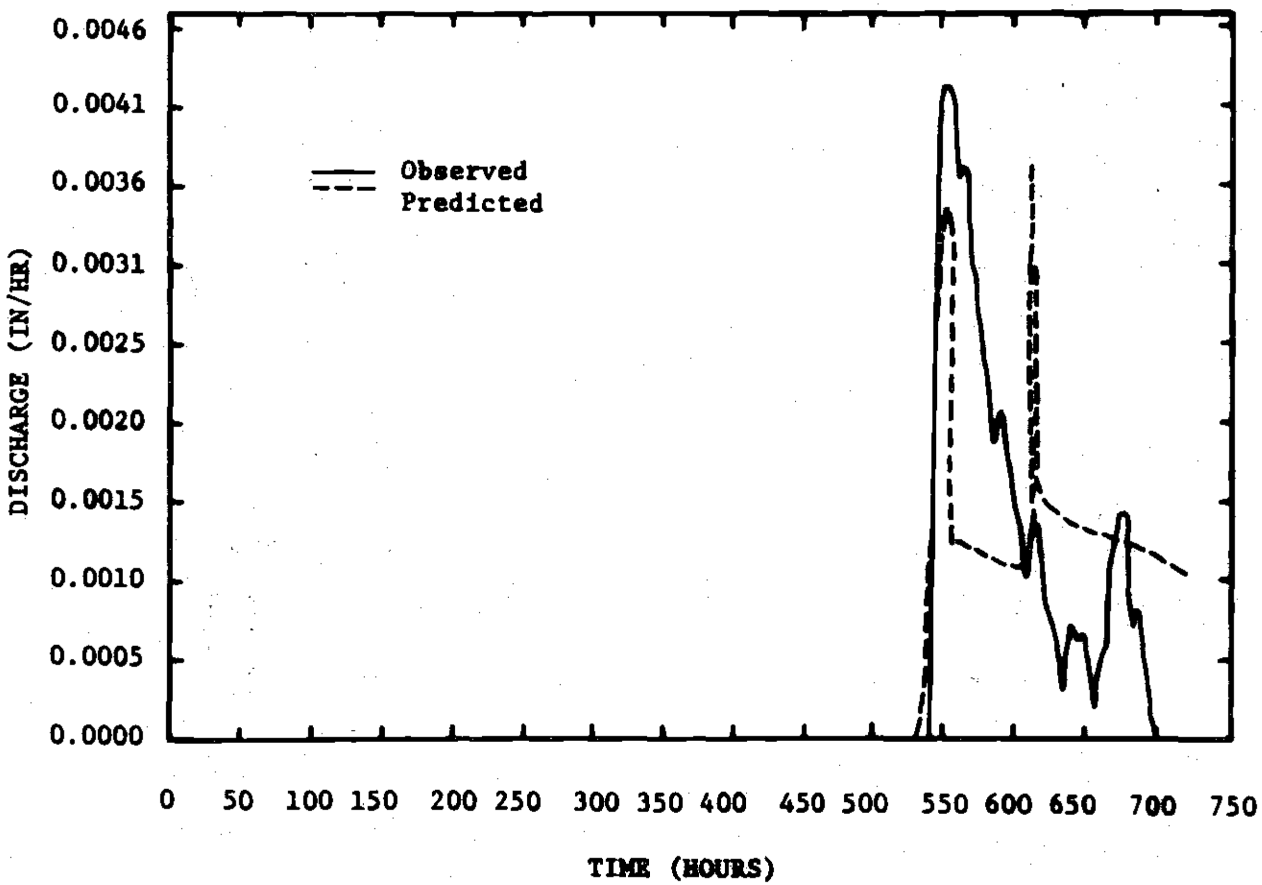

Figure 21. Subsurface Flow Event 8, December 15, 1969 to January 13. 1970

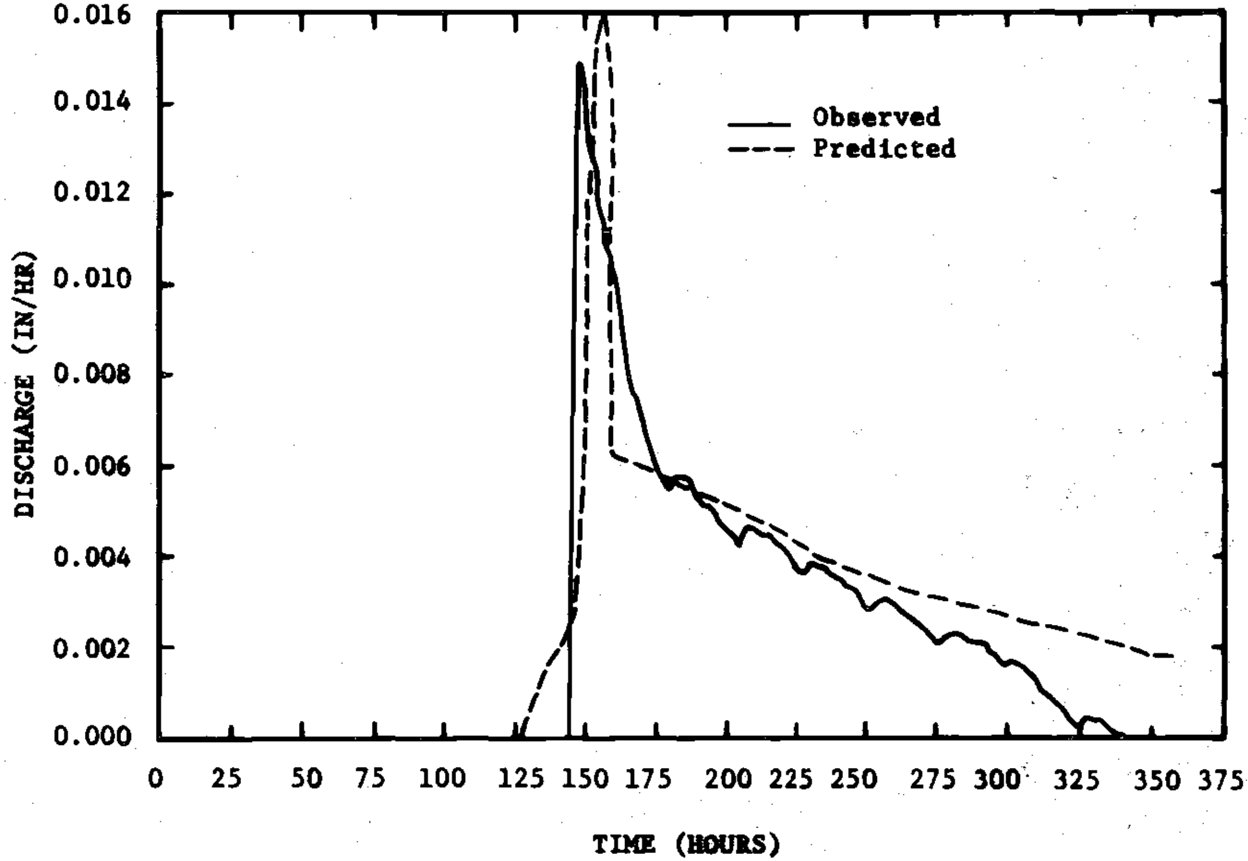

Figure 22. Subsurface Flow Event 9, January 28, 1970 to February 11, 1970

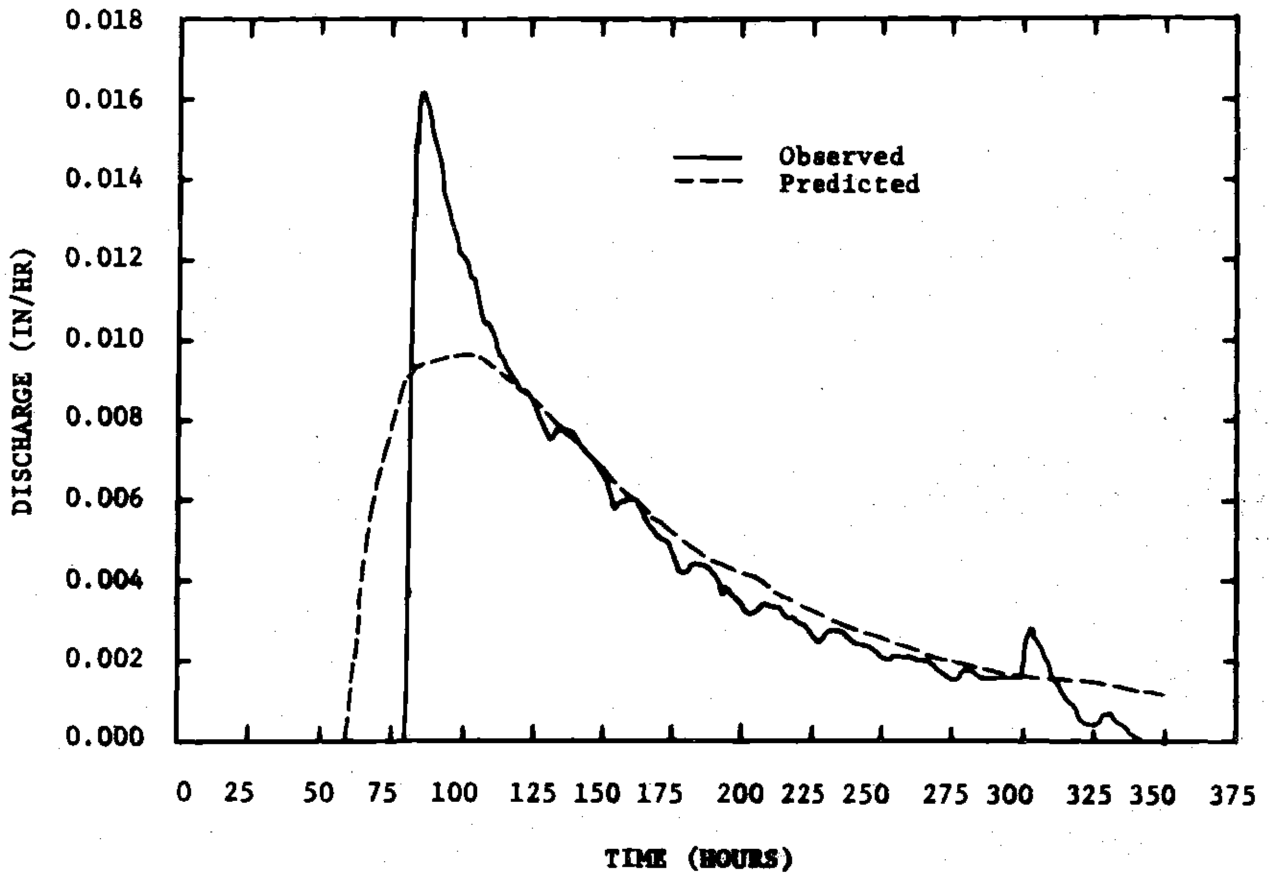

Figure 23. Subsurface Flow Event 10, February 13, 1970 to February 27, 1970

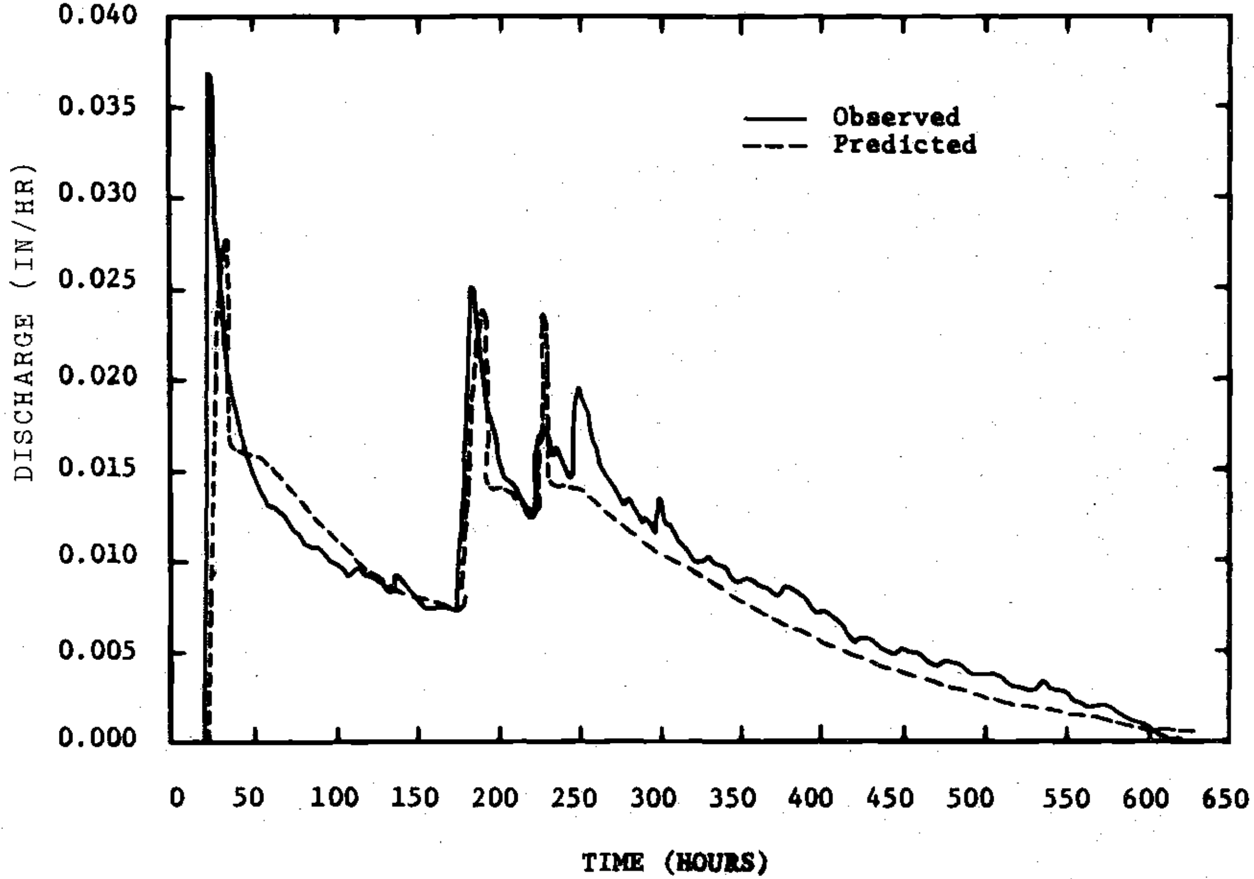

Figure 24. Subsurface Flow Event 12, March 19, 1970 to April 15, 1970

given in Table 15. On the average, the peak rates were predicted with a 29 percent error and the error in the time of the peak was 6 hours. Since the peaks were always predicted late, the latter error represents a bias of 6 hours. Event volumes were predicted with an average error of 13 percent. As can be seen in Table 16, the volumes for all but two events were over predicted.

The preceeding comparisons indicated the model's ability to predict the subsurface flow hydrograph. In addition, the following soil moisture comparison is a check on the moisture accounting portion of the model. The soil moisture data from tube Z1 was used for the lower area comparison and the soil moisture from tube Z3 was used for the upper area comparison. A summary of the associated soil moisture errors are given in Table 17. On the average, the soil moisture in all zones was predicted with a 15 percent error.

The average soil moisture error for the upper zones was 16 percent with an error range of 0 to 50 percent. The model never predicted soil moisture storage greater than the porosity. Usually, the soil moisture in the upper zone for the upper area was over estimated while that for the lower area was underestimated. The largest errors were found to occur immediately before or after a rain. Since the actual time of day the soil moisture measurements were taken was not recorded (assumed to be noon), a portion of the large errors can be attributed to this. Omitting the values thought to be in error reduced the average error to approximately 11 percent. The reasonable prediction of soil moisture indicates that the vertical drainage function and the evapotranspiration functions produce the

Table 15. Summary of Hydrograph Peak Errors

Event No	Number of Peaks	Rate Errors of Peaks: Average in/hr	Average %	Range: Maximum in/hr	Maximum %	Range: Minimum in/hr	Minimum %	Timing Errors of Peaks: Average hrs	Range: Maximum hrs	Range: Minimum hrs
1	1	0.0006	-29					2		
2	1	0.024	-20					2		
4	3	0.011	37	0.0124	83	0.0109	6	4	8	1
5	2	0.0028	60	0.0032	80	0.0025	40	3	4	2
6	6	0.0028	27	0.0088	66	0.0048	12	9	11	6
7	1	0.0000	1					9		
8	1	-0.0011	-26					2		
9	1	0.009	6					8		
10	1	-0.0065	-40					7		
12	4	0.0049	20	0.006	30	0.0016	6	6	9	3

Table 16. Summary of Event Volume Errors

Event No.	Event Volume Observed inches	Predicted inches	Error inches	Error %
1	0.043	0.046	0.003	7
2	0.780	0.888	0.108	14
4	4.427	5.133	0.706	16
5	1.344	1.489	0.145	11
6	9.301	7.771	1.530	-16
7	2.103	2.270	0.167	8
8	0.249	0.266	0.017	7
9	0.790	0.916	0.126	16
10	1.228	1.347	0.119	10
12	5.508	4.906	0.602	-11

Table 17. Summary of Soil Moisture Errors

Event No.	Number of Readings	Upper Area 0-12 inch zone Errors Average in	%	Upper 0-12 Range Maximum in	%	Upper 0-12 Range Minimum in	%	Upper Area 12-36 inch zone Errors Average in	%	Upper 12-36 Range Maximum in	%	Upper 12-36 Range Minimum in	%	Lower Area 0-12 inch zone Errors Average in	%	Lower 0-12 Range Maximum in	%	Lower 0-12 Range Minimum in	%	Lower Area 12-36 inch zone Errors Average in	%	Lower 12-36 Range Maximum in	%	Lower 12-36 Range Minimum in	%
1	1	0.16	12					1.30	21					0.17	7					1.72	27				
2	3	0.04	3	0.09	7	0.01	1	0.28	5	0.55	9	0.08	1	0.40	17	0.47	20	0.29	12	1.00	15	1.23	19	0.85	13
4	11	0.17	11	0.41	28	0.05	4	0.48	8	1.03	17	0.03	1	0.31	30	0.48	24	0.04	2	1.33	16	2.05	30	0.76	12
5	2	0.32	29	0.38	38	0.26	20	0.46	7	0.56	9	0.35	6	0.07	3	0.10	4	0.04	2	1.21	19	1.29	20	1.12	18
6	13	0.26	25	0.48	52	0.08	5	1.08	18	1.69	20	0.76	12	0.11	5	0.24	10	0.01	0	0.62	24	2.30	33	1.12	17
7	1	0.14	14					0.78	14					0.04	2					0.56	8				
8	0																								
9	2	0.16	13	0.30	24	0.01	1	0.97	17	1.25	22	0.69	12	0.33	19	0.42	23	0.24	15	0.98	14	0.14	17	0.78	12
10	5	0.22	16	0.38	28	0.05	4	0.42	7	1.02	17	0.02	0	0.32	17	0.58	30	0.18	9	1.11	17	1.48	22	0.86	13
12	11	0.12	14	0.27	30	0.03	2	0.30	5	0.65	11	0.18	3	0.12	5	0.28	14	0.00	0	0.54	7	1.02	15	0.19	3

desired effects; however, there were not enough soil moisture measurements during vertical drainage to check the function directly.

The average soil moisture error for the lower zones was 14 percent with an error range of 0 to 34 percent. The soil moisture predicted by the model never exceeded the porosity; however, soil moisture in both areas was almost always overestimated. Since the model is predicting soil moisture for an area, the comparison with data at only one point might be misleading. For example, the soil moisture taken at tube Z2 in the lower levels is on the average 0.50 inches higher than that at Z1, indicating spatial variability.

The soil moisture data also indicates that not enough moisture is being lost from the lower zone since the model over estimates both the soil moisture and event volumes. Thus, the evapotranspiration function for the lower zone is incorrect or the model needs a seepage function for the clay layer. Comparison of the measured daily evapotranspiration (Table 6) with the evapotranspiration predicted by the model indicated the evapotranspiration function was performing correctly. Thus a small seepage rate for the clay layer is needed in the model. To determine whether a constant seepage rate for the clay layer would significantly alter the preceeding results, a constant seepage rate of 0.015 inches per day was added to the model. Seepage was only allowed to occur when the soil moisture storage was above the threshold for initiating horizontal flow.
The addition of the constant seepage rate did not significantly change the previous model results except that the predicted and observed soil moisture was brought into better agreement with an average

error of about 7 percent in the lower soil zones. A constant seepage rate is not the best assumption since seepage would vary according to the amount of moisture in the zone; however, the introduction of such a function would complicate the optimization of the subsurface model; therefore, a seepage function was not added to the model.

Sensitivity

The results of the fittings were discussed above with respect to the fitting statistics and the hydrologic characteristics. The following discussion will pertain to the interpretation of the numerical values of the optimized parameters. Inspection of the optimized parameters in Table 14 shows that parameters b_{11}, b_{12}, and b_{21} went to their upper limits for almost all events. Also, the parameters c and d were fairly stable.

A sensitivity analysis was performed to determine those parameters which have the greatest influence on the model. One parameter at a time was changes ± 5 and ± 10 percent with all other parameters held constant at their optimized value. The value of the objective function was calculated for each change. The sensitivity analysis for each event gave similar results and a typical graph showing the objective function divided by the optimized objective function of each parameter is shown in Figure 25. Sensitivity analysis gave some important insight into the parameters. First is the obvious sensitivity of parameter b_{22}. Second is the almost insensitive nature of parameters c and d. The other parameters gave a varying degree of senstivity.

The persistent insensitivity of the parameters c and d and the consistency of parameters b_{11} and b_{21} going to their upper limits

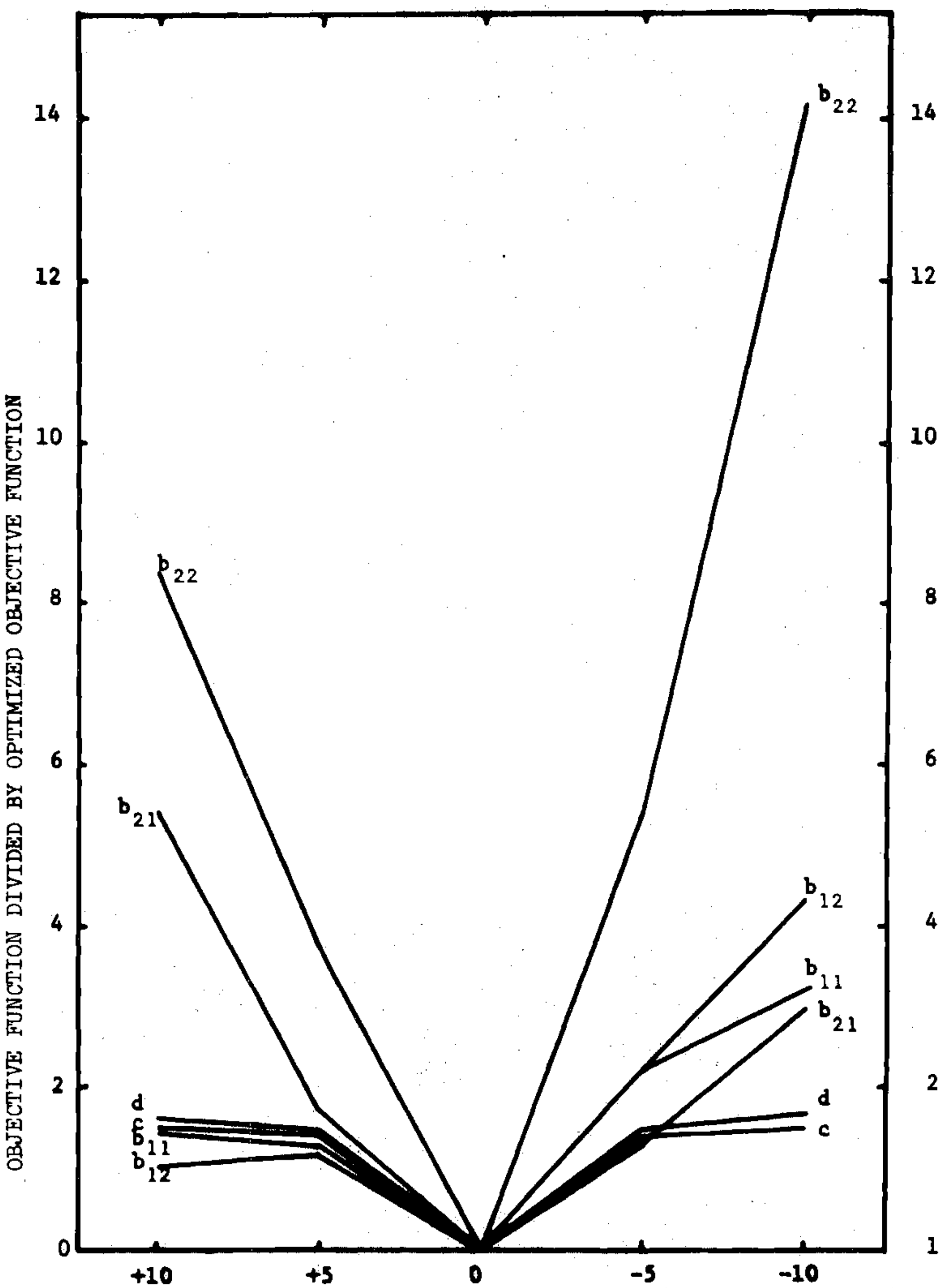

Figure 25. Relative Sensitivity of the Model Parameters for Event 2

leads to the question of how important these four parameters are with respect to the subsurface flow model. To examine this question, the model was simplified by fixing values of four parameters at the value determined by averaging across the optimized values. This yielded a value for b_{11}=0.56, b_{21}=0.59, c=0.055, and d=0.033. The simplified two-parameter model was optimized and the results of this optimization are given in Table 18. The results are quite similar to those presented for the six-parameter model in Table 14. The two-parameter model produced an average correlation coefficient of 0.83 and a standard error of estimation of 53 percent. The event volumes were usually predicted too high with an average error of 17 percent. The peak rates were usually overestimated with an average error of 36 percent and an average delay of 5 hours. The soil moisture in the upper levels was predicted with an average error of 16 percent, and the lower levels with an average error of 11 percent. Comparing the prediction statistics and the predicted hydrologic characteristics for the two-parameter model with the six-parameter model indicates that the differences are not significant. Thus, it appears the reduction of parameters is warranted. A sensitivity analysis of the simplified two-parameter model indicated that b_{22} was much more sensitive than b_{12}. This was expected since the lower area is the controlling area for outflow.

Verification

Verification of the proposed subsurface flow model involves simulation of the subsurface flow hydrographs for the four events not used in calibration. These events are 3, 11, 13, and 14. Since sensitivity analysis and calibration indicated the proposed six-parameter model could be simplified to a two-parameter model, verification is performed on the two-parameter model. The average parameter values obtained from the calibration (Table 18 b_{12}=0.419 and b_{22}=0.423) were used for these simulations. The predicted and observed hydrographs for the four verification events are shown in Figures 26 through 29. The agreement in the preceding figures is considered satisfactory, especially since the two sensitive parameters were fixed at the average optimized values.

For the four verification events the model produced an average correlation coefficient of 0.77 and an average standard error of estimation of 60 percent. The water yields were usually overestimated with an average error of 15 percent. The soil moisture was predicted with an average error of 12 percent with the upper zone having an average error of 13 percent and the lower area having an average error of 11 percent. The peak rates were predicted with an average error of 51 percent; however, examination of the peak errors indicated that two peaks caused this large average error while the others have an average error of 29 percent. The peaks were estimated 4 hours late on the average. The statistics for the verification events are summarized in Table 19. Even though the comparisons are not as good as the optimized events, they are satisfactory considering that the two sensitive parameters were set at average values.

Table 18. Optimized Parameters for the Simplified Subsurface Flow Model

Event No.	Optimized Parameters b_{12}	Optimized Parameters b_{22}	Correlation Coefficient	Percent Std. Error of Estimation
1	0.50	0.51	0.50	190
2	0.37	0.51	0.93	38
4	0.50	0.41	0.90	47
5	0.50	0.37	0.88	44
6	0.50	0.48	0.64	53
7	0.50	0.42	0.95	43
8	0.50	0.51	0.42	81
9	0.50	0.44	0.84	75
10	0.14	0.42	0.65	87
12	0.34	0.32	0.87	34
Average [1]	0.419	0.423	0.83	53

1/ Excluding events 1 and 8

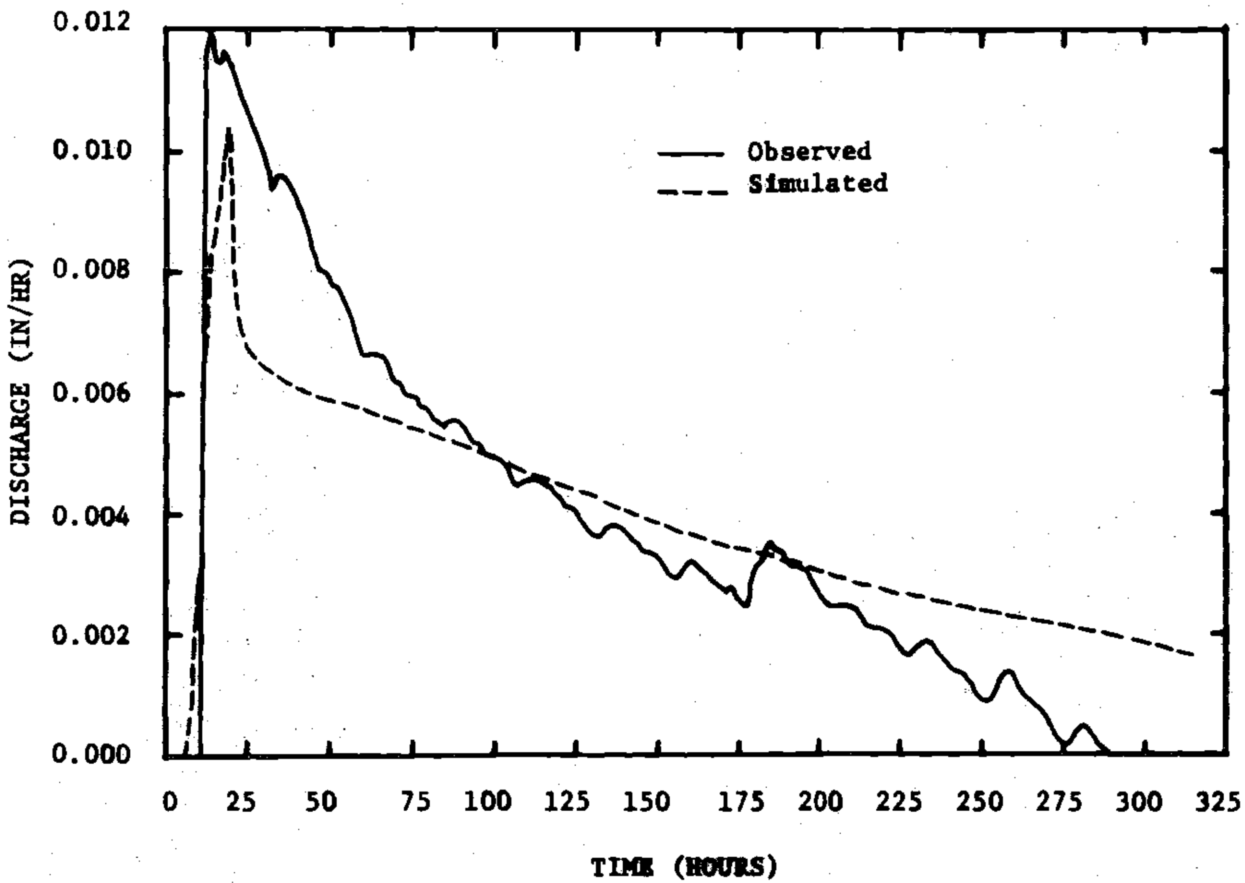

Figure 26. Subsurface Flow Event 3, January 27, 1969 to February 27, 1969

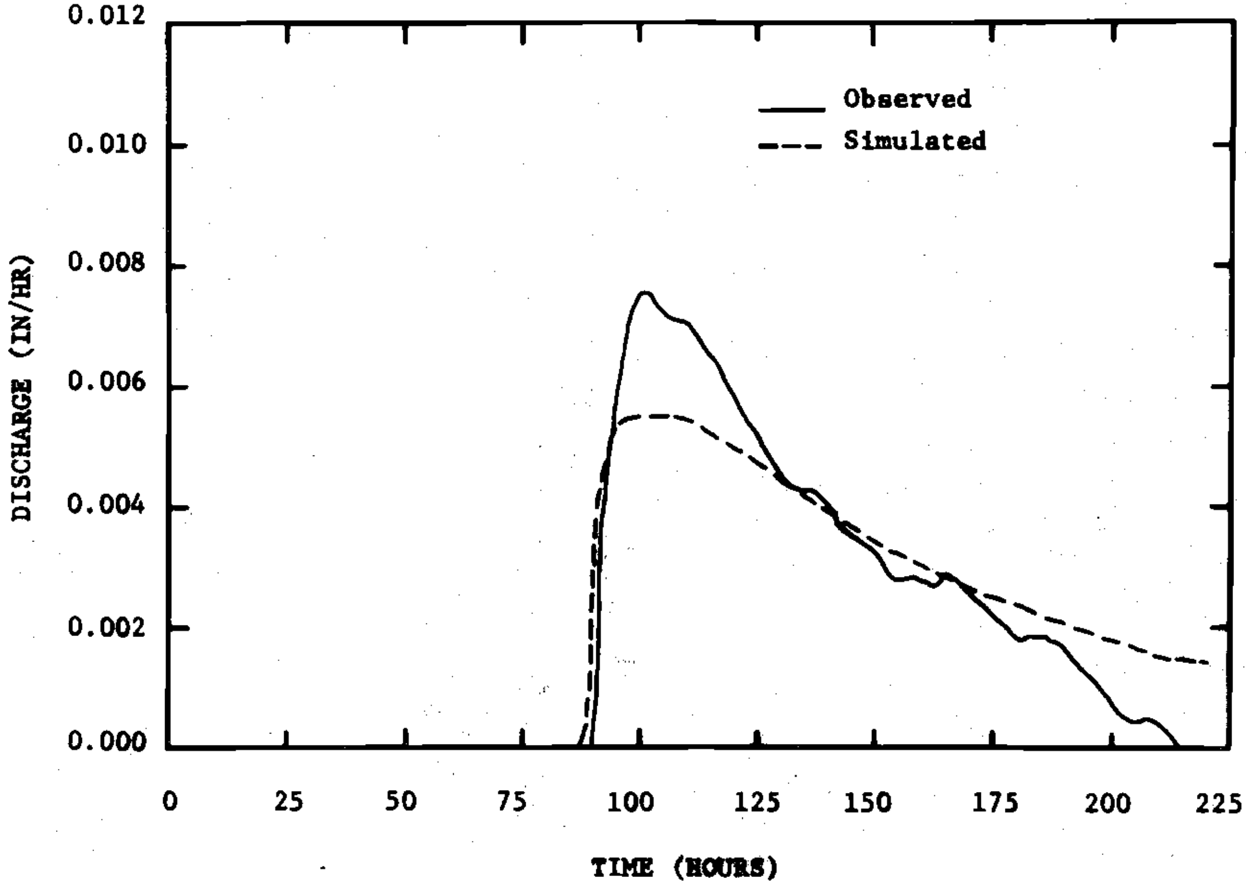

Figure 27. Subsurface Flow Event 11, March 5, 1970 to March 13, 1970

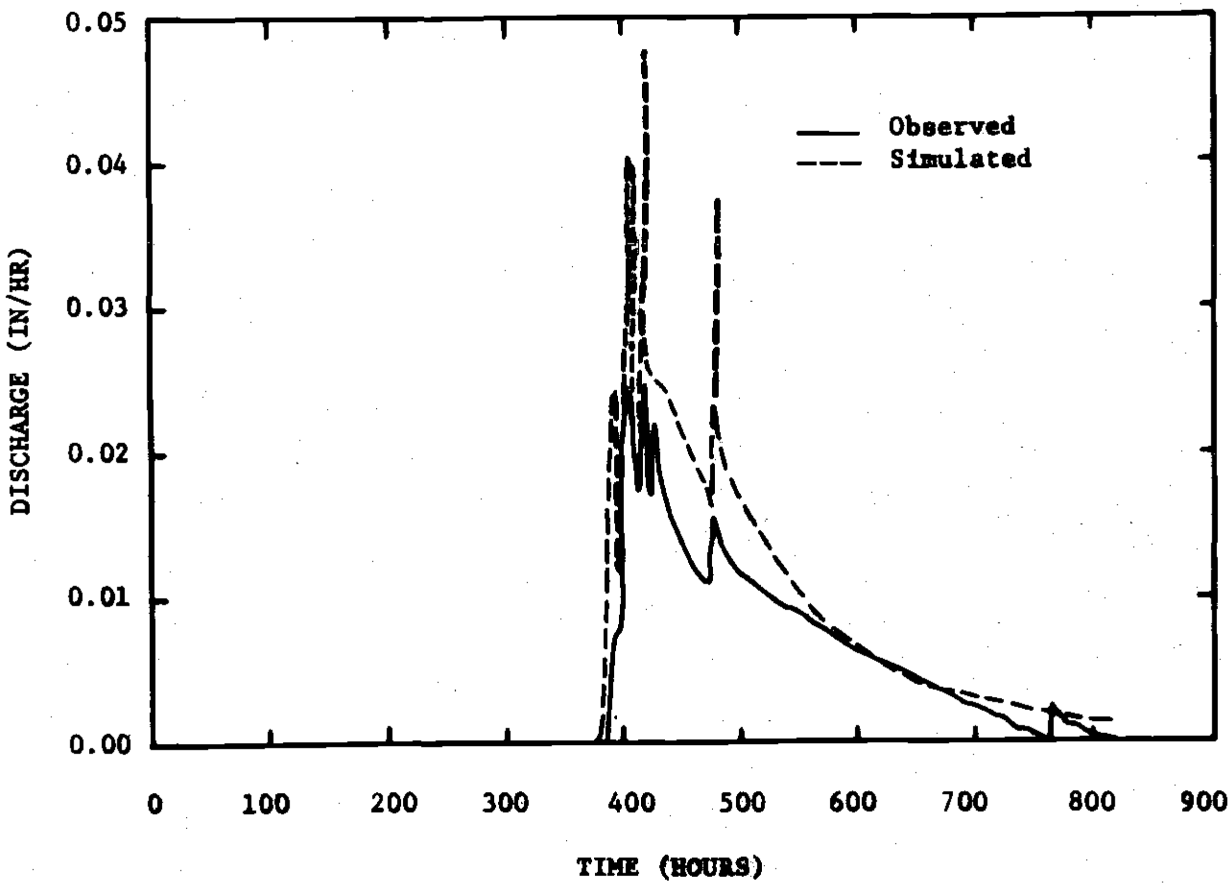

Figure 28. Subsurface Flow Event 13, May 13, 1970 to June 15, 1970

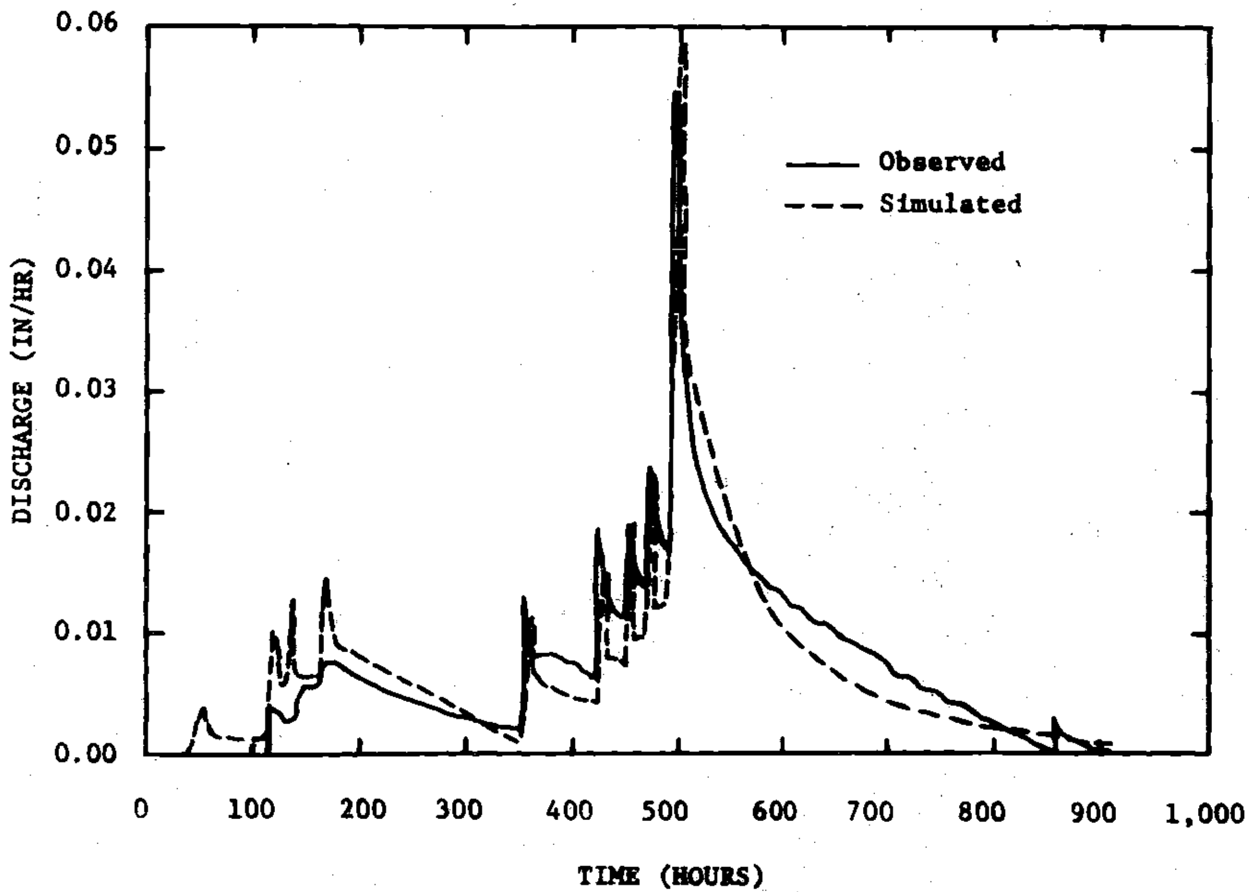

Figure 29. Subsurface Flow Event 14, August 6, 1970 to September 12, 1970

Table 19. Summary Statistics for Verification Events

Event	Correlation Coefficient	Percent Std. Error of Estimation
3	0.85	42
11	0.64	80
13	0.73	82
14	0.87	49
Average	0.77	63

Parameter Estimation

The proposed subsurface flow model simulates subsurface flow based on a set of model parameter values. Optimization can be used to estimate an appropriate set of parameter values for watersheds where subsurface flow records are available. Where no such records are available, the altervative is to estimate them from measurable physical characteristics of the watershed. This section attempts to develop relationships whereby parameter values may be estimated for ungaged watersheds. The following logic was used in developing methods for estimating the model parameters.

Equation 9 is essentially a vertical drainage function for the upper zone, with the parameters b_{11} and b_{21} controlling the drainage rates. Logically, when the upper zone is field saturated, and a rainfall amount equal to the final infiltration rate is applied, this function should produce a drainage rate equal to the final infiltration rate. Therefore, the parameters b_{11} and b_{21} can be estimated from equation 9 using the final infiltration rate as Q_t and a soil moisture storage (S_t) equal to the field saturation, plus the hourly volume of water which will infiltrate at the final infiltration rate. Using the average final infiltration rate of 2.56 in/hr for the upper area (Appendix A average of 7 runs at location 17) and 3.19 in/hr for the lower area (Appendix A average of 6 runs at location 16), the above proposed relationship produced a b_{11}=0.57 and b_{21} = 0.60 which are almost equal to the average optimized values (b_{11}=0.59 and b_{21}=0.56).

The relationship defining b_{12} and b_{22} for the lower zones was not as easily determined because these parameters represent a combination of horizontal and vertical drainage and they are also interrelated with the scaling parameters c and d. The parameters b_{12} and b_{22} can be determined if flow at different soil moisture storages are known. The relationship for determining the parameter b_{12} and b_{22} is

$$\frac{Q_1}{Q_2} = \frac{c*(S_1 - a*(\tanh\ (b \times S_1)}{c*(S_2 - a*(\tanh\ (b \times S_2)} \tag{13}$$

where

Q_1 = first flow rate (in/hr)

Q_2 = second flow rate (in/hr)

S_1 = first soil moisture storage minus the soil moisture storage when drainage begins (in)

S_2 = second soil moisture storage minus the soil moisture storage when drainage begins (in)

a = available storage between the soil moisture storage when drainage begins and the maximum soil moisture storage under field conditions (in

b = drainage characteristic of the soil (in^{-1})

tanh = hyperbolic tangent

c = scaling parameter

Equation 13 is developed from equation 10. The data to solve the above equation can be easily obtained from infiltration experiments if soil moisture storage is measured at various times after the ending of the applied rainfall. Such data were collected in connection with the infiltration experiments. Subtracting the soil moisture measured immediately after the end of rainfall from that measured one hour later, a lateral flow for a given storage could be determined. Equation 13 could be solved for b by using two sets of measurements. This technique produced a b_{12}=0.423 and b_{22}=0.431 which are approximately equal to the average parameter value obtained from optimization (b_{12} = 0.419 and b_{22} = 0.423). Once the lower drainage parameters b_{12} and b_{22} are known, the scaling parameter c can be determined from equation 10 by substituting a maximum subsurface flow rate (Table 13 Q_t = 0.417 in/hr) as Q_t and a soil moisture storage equal to the total field porosity as S_t. This produces a c equal to 0.066 which is approximately equal to the optimized value of 0.055. In areas where shallow subsurface flow is the major component of streamflow, the maximum flow rates can be obtained from streamflow records in the general area. The scaling parameters are postualted to represent the fast and slow drainage rates exhibited by the subsurface flow hydrograph and should be related to each other. Since the volume of water drained from a saturated soil core in 15 minutes is an estimate of the fast draining pores and the volume of water drained between 15 minutes and 15 hours is an estimate of the slow draining pores (30), the ratio of these values should be an estimate of the ratio of parameter c to d. The drainage data given in Table 4 yielded a ratio of 0.52; thus producing a d equal to 0.035 which approximates the average optimized value of this parameter (0.033).

The above tentative relationships are presented to illustrate that the model parameters could be rationally related to watershed characteristics. These relationships might change considerably if a larger data base were obtained.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Subsurface flow and infiltration studies conducted on 10 Little River Watershed soils under artificial rain, and on one small watershed under natural rain, indicate that shallow subsurface flow was the major contributor to streamflow in the Little River Watershed. For all the souls studied, an average of about 42% of the applied rainfall became subsurface flow, with the final infiltration rate varying between 1 in/hr and 3 in/hr. The infiltration rates and shallow subsurface flow volumes illustrate a consistent relationship with soil topographic groupings classified as upland, middle and lowland, with the upland producing the greatest amount of subsurface flow and the lowland the least. On a 0.849-acre upland watershed, shallow subsurface flow accounted for 28.4% of the total precipitation for a 3-year period while surface runoff accounted for only 7% of the total precipitation. Shallow subsurface flow occurred in all months except November, with the most prominent events occurring in March and August. A semi-impermeable clay layer (B22 horizon) found at the 3- to 4-foot depth restricted vertical drainage and caused shallow subsurface flow. Since the soil and topographic conditions studied in the Little River Watershed are representative of much of the Southern Coastal Plain, it is thought that the above findings are also representative of a much larger Coastal Plain area than just the Little River Watershed.

From data on the small upland watershed and the development and testing of a macro-scale shallow subsurface flow model, several implications about the shallow subsurface flow process can be made.

1. A semi-impermeable clay layer (B22 horizon existing at a 3- to 4-foot depth is the major cause of shallow subsurface flow in sandy soils.
2. Shallow subsurface flow quantity is essentially a function of the soil water storage above the clay layer.
3. To describe the spacial characteristics of the shallow subsurface flow process the watershed needs to be divided into an upland and lowland area. The upland area acts as a receiver of water which drains relatively fast to the lowland which stores water longer and releases it much slower to streamflow.
4. Horizontal flow began at a moisture content corresponding to the moisture held at about 0.1 bar tension.
5. Field saturation of snady soils was determined to be 85% of the total porosity of the soil.
6. The hyperbolic tangent proved acceptable as a macro-scale shallow subsurface flow routing function. The parameters associated with the hyperbolic tangent could be related to watershed characteristics.
7. Hydraulic characteristics of the soil indicated that the sandy soil should be divided into two vertical zones. The

upper zone would be the top 12 to 18 inches. The moisture content in this zone is strongly influenced by evapotranspiration. The lower zone would be the soil profile between the top zone and the clay layer. This zone is predominately influenced by the shallow subsurface flow process.

Recommendations for Further Study

Since the shallow subsurface flow can be a sizable component of streamflow the need exists to develop a watershed description system that could be used to assess the magnitude of the shallow subsurface flow. This study identified some hydrologic and soil characteristics which are important shallow subsurface flow descriptors. In particular, soil and hydrologic characteristics seem to vary with topographic location relative to drainage patterns. Seepage moves the finer materials downslope leaving the coarse material upslope. Thus future effects might be directed at developing a descriptive system expanding on this phenomena.

Pertaining to the proposed descriptive system and a better understanding of the macro-scale shallow subsurface flow process, the following recommendations are made.

1. Development of simple field methods for measuring the hydraulic properties of the soil are needed so that the hydraulic soil properties of the watershed can be better characterized.

2. More detailed field studies need to be conduced to develop a method for describing the field variability of the hydraulic properties of the soil. For transferability, these studies shouls be performed on benchmark soils.
3. Similar studies for understanding the macro-scale shallow subsurface flow process should be conducted in other areas of the country which have soil characteristics that cause singificant amounts of shallow subsurface flow. The studies should be more elaborate than this study in the measurement of soil water.
4. Development and testing of macro-scale shallow subsurface flow models (like the one developed in this study) should be conducted.

APPENDIX A

INFILTRATION DATA

Location Code - 01011D

Location	Soil Type	Plot	Soil Moisture Condition
01	01	1	D

Soil Type: Number

Number	
01	Alapaha loamy sand
02	Carnegie loamy sand
03	Cowarts loamy sand
04	Dothan loamy sand
05	Fuquay loamy sand
06	Fuquay pebbley loamy sand
07	Kershaw coarse sand
08	Leefield loamy sand
09	Robertsdale loamy sand
10	Stilson loamy sand
11	Troup sand
12	Tifton loamy sand

Plot:
1 - first plot
2 - second plot
3 - third plot
4 - fourth plot

arbitrary order for identification purposes only

Soil Moisture Condition:
D - first infiltration run on the plot
W - second infiltration run on the plot
WW - third infiltration run on the plot

TABLE A-1. Summary of Infiltration Data

Soil Series	Hydro-logic Group 1/	Cover Conditions	Location Code 2/	Soil Moisture Depth 0-12" (inches)	Soil Moisture Depth 12-36" (inches)	Total Length of Applied Rainfall (minutes)	Time from Start of Applied Rain-fall to Start of Runoff (minutes)	Rainfall Intensity (in./hr.)	Final Infiltra-tion Rate (in./hr.)	Time Between Applied Rain-fall Events (minutes)
Alapaha Loamy-Sand	D	Weeds (90%) Bare	01011D	1.17	7.48	140	3	6.73	2.26	85
			01011W	1.38	9.26	120	3	4.45	0.84	
Alapaha Loamy-Sand	D	Weeds (90%) Bare	01012D	1.01	8.97	130	4	4.57	0.48	65
			01012W	1.53	10.60	120	4	2.88	0.34	
Carnegie Loamy-Sand	C	Grass (100%)	02021D	0.37	6.36	135	7	6.61	3.25	60
			02021W	1.28	9.18	122	9	5.53	2.07	
Carnegie Loamy-Sand	C	Grass (100%)	02022D	0.47	6.89	150	4	4.69	2.52	65
			02022W	1.25	9.54	110	9	3.01	1.66	
Cowarts Loamy-Sand	C	Weeds (80%) Bare	03031D	0.58	8.87	130	8	5.17	3.00	85
			03031W	1.39	10.45	120	5	6.01	4.57	
			03031WW	1.58	10.41	40	2	5.17	3.01	10
Cowarts Loamy-Sand	C	Weeds (50%) Bare	03032D	0.48	7.58	150	30	3.37	3.17	80
			03032W	1.27	9.31	90	6	4.81	1.63	
			03032WW	1.76	10.11	50	8	3.37	2.12	30
Cowarts Loamy-Sand	C	Weeds (60%) Corn	16031D	0.73	8.62	140	4	4.45	3.48	63
			16031W	1.36	9.79	147	3	6.50	2.90	
Cowarts Loamy-Sand	C	Weeds (60%) Corn	16032D	0.80	9.56	150	15	4.45	4.21	85
			16032W	1.56	12.80	135	2	6.50	3.57	
Cowarts Loamy-Sand	C	Weeds (80%) Corn	16033D	0.79	10.03	163	7	4.33	4.04	50
			16033W	1.72	11.99	120	4	2.88	0.91	
Cowarts Loamy-Sand	C	Grass (100%)	17031D	0.46	6.97	150	4	4.33	4.08	65
			17031W	1.08	8.92	122	8	6.25	2.06	
Cowarts Loamy-Sand	C	Grass (100%)	17032D	0.39	6.50	155	7	4.57	2.60	70
			17032W	1.21	9.31	135	6	6.25	1.20	
Cowarts Loamy-Sand	C	Grass (100%)	17033D	0.44	6.44	130	4	2.76	2.62	60
			17033W	1.07	8.65	100	6	5.29	2.88	
			17033WW	1.27	9.29	70	8	2.76	2.52	25
Dothan Loamy-Sand	B	Bare (80%) Weeds	04041D	0.28	4.83	180	10	4.69	3.82	60
			04041W	1.35	9.30	120	6	3.37	2.74	

1/ SCS Hydrologic Classification (22).
2/ See Appendix I for explanation of Location Code.

Soil Series	Hydro-logic Group 1/	Cover Conditions	Location Code 2/	Soil Moisture Depth 0-12" (inches)	Soil Moisture Depth 12-36" (inches)	Total Length of Applied Rainfall (minutes)	Time from Start of Applied Rain-fall to Start of Runoff (minutes)	Rainfall Intensity (in./hr.)	Final Infiltra-tion Rate (in./hr.)	Time Between Applied Rain-fall Events (minutes)
Dothan	B	Bare(80%)	04042D	0.52	6.85	120	5	4.81	3.03	60
Loamy-Sand		Weeds	04042W	1.32	9.43	120	5	6.37	2.43	
Fuquay	B	Bare(50%)	05051D	0.31	5.21	177	5	4.69	2.09	70
Loamy-Sand		Weeds	05051W	1.43	8.86	145	30	3.25	3.15	
Fuquay	B	Bare(50%)	05052D	0.43	4.66	120	4	6.25	3.22	65
Loamy-Sand		Weeds	05052W	1.36	8.65	105	7	5.17	1.32	
Fuquay Pebbly	B	Grass(80%)	06061D	0.84	6.98	163	3	4.69	3.77	60
Loamy-Sand		Bare	06061W	1.24	8.27	92	3	4.45	2.81	
Fuquay Pebbly	B	Grass(80%)	06062D	0.73	6.59	163	12	2.64	2.31	61
Loamy-Sand		Bare	06062W	1.32	8.56	89	4	4.33	3.17	
Fuquay Pebbly	B	Grass(80%)	06064D	0.84	7.54	120	9	3.13	2.36	30
Loamy-Sand		Bare	06064W	1.41	8.49	305	2	6.25	2.40	
Kershaw	A	Bare(60%)	07071D	0.19	1.71	130	7	6.13	6.11	35
Coarse Sand		Weeds	07071W	1.25	7.07	105	12	6.13	6.08	
Kershaw	A	Bare(60%)	07072D	0.18	1.93	265	4	6.25	6.23	
Coarse Sand		Weeds								
Leefield	C	Weeds(80%)	08081D	0.40	5.03	120	2	6.50	1.93	100
Loamy-Sand		Bare	08081W	1.32	8.87	100	5	5.17	1.08	
Leefield	C	Weeds(80%)	08082D	0.49	5.64	150	9	4.81	2.79	65
Loamy-Sand		Bare	08082W	1.44	8.30	140	14	2.38	3.00	
Robertsdale	C	Weeds(70%)	09091D	0.92	7.30	120	4	4.81	0.91	60
Loamy-Sand		Bare	09091W	1.24	8.69	120	4	3.25	0.89	
Robertsdale	C	Weeds(80%)	09092D	0.96	7.67	120	2	4.81	1.11	65
Loamy-Sand		Bare	09092W	1.30	8.97	150	2	6.73	1.21	
Stilson	B	Weeds(50%)	10101D	0.43	5.58	115	4	6.25	2.65	60
Loamy-Sand		Bare	10101W	1.42	9.19	91	8	5.05	1.15	
Stilson	B	Weeds(50%)	10102D	0.44	5.68	180	6	4.93	3.15	75
Loamy-Sand		Bare	10102W	1.41	9.01	108	11	3.00	1.90	
Tifton	B	Weeds(90%)	13122D	0.61	7.72	120	7	6.13	3.58	60
Loamy-Sand		Bare	13122W	1.28	9.50	125	5	4.57	2.45	
Tifton	B	Bare(90%)	14121D	0.84	8.32	120	6	4.69	1.75	60
Loamy-Sand		Weeds	14121W	1.38	10.25	120	4	6.37	0.12	

Soil Series	Hydro-logic Group 1/	Cover Conditions	Location Code 2/	Soil Moisture Depth 0-12" (inches)	Soil Moisture Depth 12-36" (inches)	Total Length of Applied Rainfall (minutes)	Time from Start of Applied Rain-fall to Start of Runoff (minutes)	Rainfall Intensity (in./hr.)	Final Infiltra-tion Rate (in./hr.)	Time Between Applied Rain-fall Events (minutes)
Tifton Loamy-Sand	B	Bare(90%) Weeds	14122W	1.36	10.41	120	8	2.74	0.58	
Tifton Loamy-Sand	B	Weeds(90%) Bare	15121D	0.58	8.28	120	4	4.69	2.28	60
			15121W	1.63	10.59	120	4	6.37	0.89	
Tifton Loamy-Sand	B	Weeds(90%) Bare	15122D	0.38	4.72	120	4	4.81	3.61	60
			15122W	0.85	6.37	120	5	2.64	1.82	
Troup Sand	A	Grass(100%)	11111D	0.44	6.40	133	4	4.57	1.83	63
			11111W	1.40	9.18	110	5	6.50	1.26	
Troup Sand	A	Grass(100%)	11112D	0.46	6.04	150	5	2.64	2.40	60
			11112W	1.13	8.46	122	5	4.57	1.68	
Troup Sand	A	Grass(100%)	11113D	0.46	4.92	120	3	5.17	4.16	63
			11113W	1.10	7.94	120	17	2.76	2.33	
Troup Sand	A	Weeds(60%) Bare	12112D	0.97	5.13	150	3	6.25	2.79	78
			12112W	1.72	8.80	90	6	6.25	1.73	
Troup Sand	A	Weeds(80%) Bare	12113D	1.10	7.62	150	6	6.50	2.17	76
			12113W	1.52	9.75	88	4	2.88	1.30	
Troup Sand	A	Weeds(60%) Bare	12114D	1.42	11.22	203	4	3.85	1.73	76
			12114W	1.60	13.19	60	2	3.85	1.01	

APPENDIX B

CALIBRATION OF INSTRUMENTATION

V-Notch Weir

A v-notch (90-degree) weir was used for subsurface flow measurement. The weir has a maximum head of 0.50 foot. Field calibration data was collected by the volumetric method for a head range of 0 to 0.25 foot. The data was plotted on log-log paper with head vs. discharge and it was found to form two straight lines was chosen visually as a head of 0.047 foot. A least squares linear regression was computed on both lines with the following results:

$0 \leq h \leq 0.047'$

$$Q = 39.306 \times h^{3.397} \qquad \text{(B.1)}$$

Correlation Coeff = .9978

Sample Size = 50

$0.047' < h \leq 0.250'$

$$Q = 4.891 \times h^{2.717} \qquad \text{(B.2)}$$

Correlation Coeff = .9973

Sample Size = 137

where

h = head in feet

Q = discharge cfs

It is assumed that equation 2 will hold true for all heads above 0.25 foot. The division of the calibration data into two straight lines was attributed to the fact that below a head of 0.047-foot surface tension plays a major role and above 0.047 foot it does not.

H-Flume

A 1-foot H-flume was used for surface runoff measurements. The calibration curve originally developed for the flume by L. L. Harrold and D. B. Krimgold (16) was rechecked in the field by the volumetric method. It was found that, below a head of 0.09 foot, measured discharge values were lower than those reported by Harrold and Krimgold. This shift of the rating is probably due to the approach conditions. The rating table used at Station Z is shown in Table B.1.

Neutron Probe Calibration

A Troxler model 200-B scaler and model 104-A depth probe with a 100 mc. 241 Am-Be neutron source were used to measure soil water. The probe was rebuilt by the manufacturer in the middle of the study, thus yielding two

TABLE B-1.--Rating Table for Type H-Flume, 1.0 Foot Deep

Head	00	.01	.02	.03	.04	.05	.06	.07	.08	.09
Feet										
0.	0.000 1/	.0002	.0005	.0010	.0022	.0036	.0053	.0071	.0090	.0124
.1	.0150	.0179	.0211	.0246	.0284	.0324	.0367	.0413	.0462	.0515
.2	.0571	.0630	.0692	.0758	.0827	.0900	.0976	.1055	.1138	.1226
.3	.132	.141	.151	.161	.172	.183	.194	.206	.218	.231
.4	.244	.257	.271	.285	.300	.315	.331	.347	.364	.381
.5	.398	.416	.434	.453	.472	.492	.512	.533	.554	.576
.6	.598	.621	.644	.668	.692	.717	.743	.769	.796	.823
.7	.851	.880	.909	.939	.969	1.000	1.031	1.063	1.096	1.129
.8	1.16	1.20	1.23	1.27	1.30	1.34	1.38	1.41	1.45	1.49
.9	1.53	1.57	1.61	1.66	1.70	1.74	1.78	1.83	1.87	1.92

1/ Flow values in cubic feet per second

factory calibration curves for the period of study. The factory calibration curves are given in Table B.2.

Standard 2-inch O.D. (outside diameter) aluminum irrigation tubing was used for access tubes. These tubes were installed into snug-fitting holes predrilled by a power-driven flight auger cased in 1.9-inch O.D. thin-wall steel tubing. All access tubes were installed at least a month before they were used for measuring soil water.

The procedure used for field calibration was to relate volumetric soil water measurements to the ratio of neutron probe counts and standard count. One-minute neutron probe counts were taken at 6-inch intervals to a depth of 36 inches. The soil profile descriptions (30) did not indicate drastic profile changes in the top 36 inches; thus, a constant depth increment was considered to be satisfactory.

Soil samples for gravimetric soil water determination were taken with an orchard auger (fragmented sample) from two holes at the same time neutron measurements were made. The holes were located within a radius of 2- to 4-feet of the neutron probe access tube. The 2- to 4-foot radius for gravimetric sampling was chosen so as not to destroy the site. The samples were taken by 3-inch increments to a total depth of 42 inches, placed in soil moisture cans, and brought into the laboratory and

TABLE B-2.--Summary of Calibration Curves

Period of Use	Type of Calibration Curve	Coefficients of Calibration Curve[1/] y = a + bx a	b
5-11-68 to 9-23-69	Factory	-6.082	44.723
	Field	-4.999	29.985
9-24-69	Factory	-5.433	40.241
	Field	-0.037	24.771

1/ y = Percent soil water by volume
x = Ratio of neutron probe count and standard count

weighed. They were then dried in a forced-draft oven at 105°C. for at least 24 hours and weighed again. Tests on further drying beyond 24 hours established that additional loss of water was negligible. Soil water was initially calculated as percent of dry weight and converted into percent by volume by use of bulk density data previously obtained for each soil horizon at each specific site (44). A single volumetric soil water value was determined for each neutron-value reading by averaging the volumetric data for the 6-inch thick soil layer centered at the same depth as the neutron reading.

Various least squares analysis were performed to determine the field calibration curves given in Table B-2. For the details of these analyses, see Rawls and Asmussen (36).

APPENDIX C.

```
*********** TWO PARAMETER PROGRAM ***********

C     PATSEAR-PATTERN SEARCH FOR OPTIMUM OF OBJECTIVE FUNCTION
C     RALPH F. GREEN      HYDROLOGIC RESEARCH & ANALYSIS STAFF
C     HYDRAULIC DATA BRANCH      DIV OF WATER CONTROL PLANNING      TVA
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION PAR(20),BPAR(20),TPAR(20),OBSY(1700),PREDY(1700),
     1TITLE(10),SS(2),LPAR(20),DR(20),IEXPLR(20),PCT(20),D(20),CHANGE(20
     2),ERR(1700) ,WGT(1700)
      DIMENSION ETH12(1700,2),ETH36(1700,2),SM12(1700,2),SM36(1700,2),
     1PERC(1700,2),RUN(1700,2),RAIN(1700)
       COMMON ETH12,ETH36,SM12,SM36,PERC,RUN,RAIN
      COMMON OBSY,PREDY,TPAR,ERR ,WGT,TITLE
C     PATSEAR-SURFAS-STATS-OPTUM-CONV ARE STORED ON DISC
C     MODEL-LIMIT-WGTING AND ANY OTHER SUBROUTINES SUPPLIED BY USER
      READ(5,12)NRUN
   12 FORMAT(I5)
      DO 1000 IRUN=1,NRUN
      READ(5,1)(TITLE(K),K=1,10)
    1 FORMAT(10A8)
      READ(5,2)NPAR,NOBS,KROUND,IOPT,TEST,DSTD
    2 FORMAT(4I5,2F5.0)
      READ(5,3)(PAR(I),I=1,NPAR)
    3 FORMAT(7F10.0)
      READ(5,4)IGEN,ISOL
    4 FORMAT(2I5)
      IF(ISOL.GE.2)GO TO 9
      READ(5,3)(DR(I),I=1,NPAR)
      IF(DSTD.NE.0.0)GO TO 7
      READ(5,3)(D(I),I=1,NPAR)
      GO TO 9
    7 DO 8 I=1,NPAR
    8 D(I)=DSTD
    9 WRITE(6,10)
   10 FORMAT('1',30X,' PATTERN SEARCH FOR OPTIMUM OF OBJECTIVE FUNCTION'
     1)
      WRITE(6,11)(TITLE(K),K=1,10)
   11 FORMAT(30X,10A8)
      WRITE(6,13)IOPT
   13 FORMAT(30X,'IOPT=',I3,3X,'OPTIMIZE ON THE FOLLOWING'/20X,' 1-SSE
     1   2-WEIGHTED SSE      3-SUM OF ABSOLUTE ERRORS      4-SUM OF PREDIC
     2TIONS')
      ISTART=1
      CALL LIMIT(PAR,LPAR,NPAR,ISTART)
      CALL MODEL(PAR,OBSY,NPAR,NOBS,ISTART,IGEN)
      CALL OPTUM(IOPT,ISTART,SST,NOBS)
      ISTART=0
      IF(IGEN.EQ.0)GO TO 18
      WRITE(6,17)(I,PAR(I),I=1,NPAR)
   17 FORMAT('0 UNIQUE PARAMETERS'/(8(I3,F12.5))///)
      READ(5,3)(PAR(I),I=1,NPAR)
   18 NROUND=0
      DO 19 I=1,NPAR
   19 IEXPLR(I)=0
      IACEL=0
      ICONV=0
      DO 20 I=1,20
      BPAR(I)=PAR(I)
   20 TPAR(I)=PAR(I)
      IF(ISOL.LT.2)WRITE(6,21)(I,D(I),I=1,NPAR)
   21 FORMAT('0 DECREMENTERS FOR DELTAS'/(10(I3,F5.2)/)//)
      WRITE(6,25)
   25 FORMAT('0 NROUND              SS      IACEL              PARAMETERS')
   30 DO 31 IPL=1,NPAR
   31 LPAR(IPL)=0
      CALL LIMIT(TPAR,LPAR,NPAR,ISTART)
      DO 32 IPL=1,NPAR
      IF(LPAR(IPL).EQ.1)TPAR(IPL)=BPAR(IPL)
   32 CONTINUE
      CALL MODEL(TPAR,PREDY,NPAR,NOBS,ISTART,IGEN)
      CALL OPTUM(IOPT,ISTART,SST,NOBS)
      WRITE(6,38)NROUND,SST,IACEL,(I,TPAR(I),I=1,NPAR)
   38 FORMAT(I5,D20.8,I3,12X,5(I3,F12.5)/(40X,5(I3,F12.5)/))
   41 IF(IACEL.EQ.0)SSB=SST
      SSR=.999999*SSB
      IF(ISOL.LT.2)GO TO 40
      ICONV=1
      SSE=SSB
      GO TO(40,250,225),ISOL
   40 IF(IACEL.EQ.0)GO TO 50
      IACEL=1
      IF(SST.LT.SSR)IACEL=2
      IF(IACEL.EQ.2)SSB=SST
      SSR=.999999*SSB
   50 DO 53 I=1,NPAR
   53 IEXPLR(I)=0
      JEXPLR=0
      NROUND=NROUND+1
      WRITE(6,38)NROUND,SSB,IACEL,(I,TPAR(I),I=1,NPAR)
      WRITE(6,57)(I,DR(I),I=1,NPAR)
   57 FORMAT(12X,'DELTAS AT BEGINNING OF ROUND'/(12X,8(I3,F12.8)))
      DO 90 IP=1,NPAR
   52 DO 60 JP=1,2
      DO 51 IPL=1,NPAR
   51 LPAR(IPL)=0
      SJP=(-1)**JP
      TPAR(IP)=TPAR(IP)+SJP*DR(IP)
      CALL LIMIT(TPAR,LPAR,NPAR,ISTART)
      IF(LPAR(IP).EQ.1)GO TO 54
      CALL MODEL(TPAR,PREDY,NPAR,NOBS,ISTART,IGEN)
   54 TPAR(IP)=TPAR(IP)-SJP*DR(IP)
      IF(LPAR(IP).EQ.1)GO TO 56
      CALL OPTUM(IOPT,ISTART,SST,NOBS)
      SS(JP)=SST
      IF(SS(1).GE.SSR)GO TO 60
      SS(2)=IDINT(SS(1))+1
      GO TO 65
```

```
 56 SS(JP)=IDINT(SSB)+1
 60 CONTINUE
 65 WRITE(6,70)IP,SSB,SS(1),SS(2)
 70 FORMAT(I10,3D20.8)
    IF(SS(1).GE.SSB.AND.SS(2).GE.SSB)GO TO 90
    TPAR(IP)=TPAR(IP)-DR(IP)
    SSB=SS(1)
    IF(SS(2).GE.SS(1))GO TO 80
    TPAR(IP)=TPAR(IP)+2.0*DR(IP)
    SSB=SS(2)
 80 IEXPLR(IP)=1
    JEXPLR=1
    SSB=.999999*SSB
 90 CONTINUE
    IF(JEXPLR.EQ.0)GO TO 97
    DO 95 I=1,NPAR
    IF(IEXPLR(I).EQ.0)DR(I)=D(I)*DR(I)
 95 CONTINUE
 97 IF(IACEL.EQ.2)GO TO 130
    IF(JEXPLR.EQ.1)GO TO 130
    DO 101 I=1,NPAR
    PAR(I)=BPAR(I)
101 TPAR(I)=BPAR(I)
    CALL CONV(NPAR,TPAR,DR,D,BIG)
    IF(BIG.LT.TEST)GO TO 210
    IF(NROUND.EQ.KROUND)GO TO 200
    IF(IACEL.EQ.1)GO TO 110
104 NROUND=NROUND-1
    DO 105 IP=1,NPAR
105 DR(IP)=D(IP)*DR(IP)
    GO TO 50
110 IACEL=0
    GO TO 50
130 DO 135 I=1,NPAR
135 CHANGE(I)=(TPAR(I)-PAR(I))*.5
    CALL CONV(NPAR,TPAR,CHANGE,D,BIG)
    IF(BIG.LT.TEST)GO TO 210
139 IF(NROUND.EQ.KROUND)GO TO 200
    DO 140 I=1,NPAR
    PAR(I)=BPAR(I)
    PPAR(I)=TPAR(I)
140 TPAR(I)=2.0*BPAR(I)-PAR(I)
    IACEL=1
    GO TO 30
200 WRITE(6,205)KROUND,TEST,SSB,(I,TPAR(I),I=1,NPAR)
205 FORMAT('0** DID NOT CONVERGE   ROUND=',I5,'   TEST=',F10.5,'   SSB
   1=',D20.8//'      PARAMETERS'/(5(I3,F12.5)))
    GO TO 220
210 WRITE(6,215)NROUND,TEST,SSB,(I,TPAR(I),I=1,NPAR)
215 FORMAT('0** CONVERGED   ROUND=',I5,'   TEST=',F10.5,'   SSB=',D20.
   18//'      PARAMETERS'/(5(I3,F12.5)))
    ICONV=1
220 ISTART=2
    WRITE(6,57)(I,DR(I),I=1,NPAR)
    WRITE(6,21)(I,D(I),I=1,NPAR)
```

```
    CALL MODEL(TPAR,PREDY,NPAR,NOBS,ISTART,IGEN)
    CALL OPTUM(IOPT,ISTART,SSB,NOBS)
    WRITE(6,10)
    WRITE(6,11)(TITLE(K),K=1,10)
    WRITE(6,13)IOPT
225 WRITE(6,230)
230 FORMAT('0      OBSERVED    PREDICTED       ERROR')
    IF(ISOL.EQ.3)GO TO 247
    WRITE(6,235)(J,OBSY(J),PREDY(J),ERR(J),J=1,NOBS)
235  FORMAT(1X,I4,3D13.5)
    IF(ICONV.EQ.1)GO TO 240
    WRITE(6,205)KROUND,TEST,SSB,(I,TPAR(I),I=1,NPAR)
    GO TO 245
240 WRITE(6,215)NROUND,TEST,SSB,(I,TPAR(I),I=1,NPAR)
245 JOPT=1
    CALL OPTUM(JOPT,ISTART,SSE,NOBS)
247 CALL STATS(NPAR,NOBS,SSE)
     CALL WBC(NOBS)
    IF(ISOL.EQ.0.OR.ISOL.EQ.3)GO TO 6000
250 CALL SURFAS(NPAR,NOBS,ICONV,IOPT)
000  CONTINUE
000 CONTINUE
300 STOP
    END
    PERCENTAGE CHANGE IN PARAMETERS
    SUBROUTINE CONV(NPAR,TPAR,DR,D,BIG)
    IMPLICIT REAL*8(A-H,O-Z)
    DIMENSION TPAR(20),DR(20),PCT(20),D(20)
    DO 103 I=1,NPAR
    IF(DABS(TPAR(I)).LT..0001)GO TO 102
    IF(D(I).GT.0.99)  GO TO 102
    PCT(I)=DABS(DR(I)/TPAR(I))
    GO TO 103
102 PCT(I)=0.0
103 CONTINUE
    BIG=PCT(1)
    DO 106 I=2,NPAR
    IF(BIG.GE.PCT(I))GO TO 106
    BIG=PCT(I)
106 CONTINUE
    RETURN
    END
    TWO PARAMETER RESPONSE SURFACE
    SUBROUTINE SURFAS(NPAR,NOBS,ICONV,IOPT)
    IMPLICIT REAL*8(A-H,O-Z)
    DIMENSION PAR(20),TPAR(20),OBSY(1700),PREDY(1700),LPAR(20)
    DIMENSION ETH12(1700,2),ETH36(1700,2),SM12(1700,2),SM36(1700,2),
   1PERC(1700,2),RUN(1700,2),RAIN(1700)
     COMMON ETH12,ETH36,SM12,SM36,PERC,RUN,RAIN
    COMMON OBSY,PREDY, PAR
    ISTART=0
    IGEN=0
    D=0.05
    N1=NPAR-1
  1 WRITE(6,510)
```

```
    5 FORMAT('1                                     TWO PARAMETER RESPONSE SURF
     1ACE'//30X,'D=',F10.5)
      DO 60 I=1,N1
      I1=I+1
      DO 60 IJ=I1,NPAR
      WRITE(6,10)I,IJ
   10 FORMAT('0 PARAMETER COMBINATIONS OF',I5,'    AND',I5,'    ABOUT OPTI
     1MUM'//'     K         PAR(I)              PAR(IJ)            SS')
      DRI=DABS(D*PAR(I))
      DRIJ=DABS(D*PAR(IJ))
      IF(DABS(PAR(I)).LT.0.00001)DRI=D
      IF(DABS(PAR(IJ)).LT.0.00001)DRIJ=D
      DO 60 K=1,8
      DO 15 IPL=1,NPAR
   15 LPAR(IPL)=0
      GO TO(21,22,23,24,25,26,27,28),K
   21 TPAR(I)=PAR(I)+DRI
      TPAR(IJ)=PAR(IJ)+DRIJ
      GO TO 30
   22 TPAR(I)=PAR(I)+DRI
      TPAR(IJ)=PAR(IJ)
      GO TO 30
   23 TPAR(I)=PAR(I)+DRI
      TPAR(IJ)=PAR(IJ)-DRIJ
      GO TO 30
   24 TPAR(I)=PAR(I)
      TPAR(IJ)=PAR(IJ)-DRIJ
      GO TO 30
   25 TPAR(I)=PAR(I)-DRI
      TPAR(IJ)=PAR(IJ)-DRIJ
      GO TO 30
   26 TPAR(I)=PAR(I)-DRI
      TPAR(IJ)=PAR(IJ)
      GO TO 30
   27 TPAR(I)=PAR(I)-DRI
      TPAR(IJ)=PAR(IJ)+DRIJ
      GO TO 30
   28 TPAR(I)=PAR(I)
      TPAR(IJ)=PAR(IJ)+DRIJ
   30 CALL LIMIT(TPAR,LPAR,NPAR,ISTART)
      DO 40 L=1,NPAR
      IF(LPAR(L).EQ.1)TPAR(L)=PAR(L)
   40 CONTINUE
      CALL MODEL(TPAR,PREDY,NPAR,NOBS,ISTART,IGEN)
      CALL OPTUM(IOPT,ISTART,SS,NOBS)
      WRITE(6,50)K,TPAR(I),TPAR(IJ),SS
   50 FORMAT(I5,2F15.6,D20.12)
   60 CONTINUE
      IF(ICONV.EQ.0)GO TO 70
      IF(D.GT.0.05)GO TO 70
      D=0.10
      GO TO 1
   70 RETURN
      END
C     COMPUTE STATISTICS OF FIT
      SUBROUTINE STATS(NPAR,N,SSE)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION OBSY(1700),PREDY(1700)
      DIMENSION ETH12(1700,2),ETH36(1700,2),SM12(1700,2),SM36(1700,2),
     1PERC(1700,2),RUN(1700,2),RAIN(1700)
       COMMON ETH12,ETH36,SM12,SM36,PERC,RUN,RAIN
      COMMON OBSY,PREDY
      SY=0.0
      SX=0.0
      SSY=0.0
      SSX=0.0
      SXY=0.0
      DO 10 I=1,N
      SY=SY+OBSY(I)
      SXY=SXY+(OBSY(I)*PREDY(I))
      SX=SX+PREDY(I)
      SSX=SSX+(PREDY(I)**2)
   10 SSY=SSY+(OBSY(I)**2)
      ATSS=SSY-((SY**2)/N)
      ASSR=ATSS-SSE
      IF(ASSR.GE.0.0)GO TO 20
      WRITE(6,15)ASSR
   15 FORMAT('0 ***** ERROR    ASSR=',D15.6)
      CORCO=0.
   20 OBSBAR=SY/N
      PREBAR=SX/N
      IF(ASSR.LT.0.)GO TO 30
      CORCO=DSQRT(ASSR/ATSS)
   30 SDEV=0.
      COEVAR=0.
      IF(N.LE.NPAR)GO TO 35
      SDEV=DSQRT(SSE/(N-NPAR))
      COEVAR=SDEV/OBSBAR
   35 SEREST=DSQRT(SSE/N)
      WRITE(6,40)
   40 FORMAT('0 STATISTICS')
      WRITE(6,50)SY,SSY,SX,SSX,SXY,SSE,ATSS,ASSR,OBSBAR,PREBAR,CORCO,SDE
     1V,COEVAR,SEREST
   50 FORMAT(5H0 SY=D15.8,6H  SSY=D15.8,5H  SX=D15.8,6H  SSX=D15.8/6H0 S
     1XY=D15.8,6H  SSE=D15.8,6H ATSS=D15.8,6H ASSR=D15.8/11H0 MEAN OBS=D
     215.8,11H MEAN PRED=D15.8,7H CORCO=D15.8,6H SDEV=D15.8/9H0 COEVAR=D
     315.8,6H SEREST=D15.8)
   60 RETURN
      END
      OPTUM--DEFINES HOW ERROR IS OPTIMIZED
      SUBROUTINE OPTUM(IOPT,ISTART,SS,NOBS)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION ERR(1700),WGT(1700),OBSY(1700),PREDY(1700),TPAR(20)
      DIMENSION ETH12(1700,2),ETH36(1700,2),SM12(1700,2),SM36(1700,2),
     1PERC(1700,2),RUN(1700,2),RAIN(1700)
       COMMON ETH12,ETH36,SM12,SM36,PERC,RUN,RAIN
      COMMON OBSY,PREDY,TPAR,ERR,WGT
      CHECK FOR READ-IN ON FIRST ROUND ONLY
      IF(ISTART.EQ.1)GO TO 200
      DO 10 J=1,NOBS
```

```
   10 ERR(J)=OBSY(J)-PREDY(J)
      SS=0.0
      GO TO(100,200,300,400),IOPT
C     SUM OF SQUARES
  100 DO 110 J=1,NOBS
  110 SS=SS+ERR(J)**2
      GO TO 900
C     WEIGHTED SUM OF SQUARES
  200 CALL WGTING(ISTART,NOBS)
      IF(ISTART.EQ.1)GO TO 900
      DO 210 J=1,NOBS
  210 SS=SS+(ERR(J)*WGT(J))**2
      GO TO 900
C     SUM OF ABSOLUTE VALUES
  300 DO 310 J=1,NOBS
  310 SS=SS+DABS(ERR(J))
      GO TO 900
  400 DO 410 J=1,NOBS
  410 SS=SS+PREDY(J)
      SS=100.0/SS
  900 RETURN
      END
C     STATION 2  SUBSURFACE FLOW  MODEL
      SUBROUTINE MODEL(PAR,PREDY,NPAR,NOBS,ISTART,IGEN)
      IMPLICIT REAL *8(A-H,O-Z)
       REAL K36,K12
      DIMENSION SMC12(6),SMC36(6),GI(70),PE(70),FTH(24),RA(24),RAIN(1700
     1),RU(6),PREDY(1700),SM12(1700,2),SM36(1700,2),
     2SME12(70),SM36E(70),SME36(70),FT12(70,4),ET36(70
     3,4),ETH12(1700,2),PERC(1700,2),PAR(20),RUN(1700,2),AREA(50),
     4ETH36(1700,2)
          DIMENSION COE(10)
       COMMON ETH12,ETH36,SM12,SM36,PERC,RUN,RAIN
      IF(ISTART.EQ.2) GO TO 40
      IF(ISTART.EQ.0) GO TO 40
C     READ INDEPENDENT AND DEPENDENT VARIABLES
C      ND = NUMBER DAYS     NS = DAY RUNOFF STARTS      NT = DAY RUNOFF STOPS
       NZ=2
       READ(5,500)SMC12(1),SMC36(1),SMC12(2),SMC36(2),AREA(1),AREA(2)
      WRITE(6,510)SMC12(1),SMC36(1),SMC12(2),SMC36(2),AREA(1),AREA(2)
  500  FORMAT(6F5.2)
  510 FORMAT(/,'  SMC12(1) - ',F5.2,'   SMC36(1) - ',F5.2,'   SMC12(2) -
     1 ',F5.2,'   SMC36(2) - ',F5.2,'   AREA(1) - ',F5.2,'   AREA(2) -
     2',F5.2,/)
       READ(5,1) ND,NS,NT
    1  FORMAT(3I3)
C     SMC12(I) = STORAGE CAPACITY (INCHES) FOR FLOW TO START 0-12 INCH DEPTH
C     SMC36(I) = STORAGE CAPACITY (INCHES) FOR FLOW TO START 12-36 INCH DEPTH
C     SM12,SM36  INITIAL SOIL MOISTURE FOR ZONES AND LEVELS
      READ(5,2)(SM12(1,I),SM36(1,I),I=1,NZ)
    2 FORMAT(6F6.2)
C     GI(I) = DAILY GROWTH INDEX FOR CROP
      READ(5,3)  (GI(I),I=1,ND)
    3 FORMAT(13F6.3)
C     PE(I) = DAILY PAN EVAPORATION IN INCHES
      READ(5,4) (PE(I),I=1,ND)
    4 FORMAT(16F5.2)
       KS=ND*24
       DO 300 I=1,KS
        PREDY(I)=0.0
       RAIN(I)=0.0
  300  CONTINUE
C     RAIN(K) = HOURLY RAINFALL
      DO 100 I= 1,ND
      READ(5,6) (RA(J),J=1,24)
    6 FORMAT(7X,24F3.2)
      DO 100 J=1,24
      K = I*24 + J - 24
      RAIN(K) = RA(J)
  100 CONTINUE
      DO 101 I=NS,NT
      DO 101 J=1,4
      READ(5,7)(RU(K),K=1,6)
    7 FORMAT(13X,6E10.5)
      DO 101 K = 1,6
      M =  I*24 +J*6 - 30  + K
      PREDY(M) = RU(K)*1.15857
  101 CONTINUE
C     1.15857 CONVERTS CFS TO INCHES PER HOUR
      RETURN
   40 CONTINUE
C     ETH(I) = HOURLY ET DISTRIBUTION FUNCTION
       ETH(1)=0.0
       ETH(2)=0.0
       ETH(3)=0.0
       ETH(4)=0.0
       ETH(5)=0.0
       ETH(6)=0.0
       ETH(7)=0.0081
       ETH(8)=0.0295
       ETH(9)=0.0606
       ETH(10)=0.0884
       ETH(11)=0.1064
       ETH(12)=0.1211
       ETH(13)=0.1309
       ETH(14)=0.1342
       ETH(15)=0.1277
       ETH(16)=0.1047
       ETH(17)=0.0655
       ETH(18)=0.0229
       ETH(19)=0.0
       ETH(20)=0.0
       ETH(21)=0.0
       ETH(22)=0.0
       ETH(23)=0.0
       ETH(24)=0.0
       COE(2)=PAR(1)
       COE(4)=PAR(2)
       COE(6)=0.60
       COE(8)=0.57
```

```
      COE(1)=1.75
     COE(3)=2.05
      COE(5)=1.70
      COE(7)=2.00
C     COMPUTE PREDICTIONS
     DO 102 I = 1,ND
     DO 103 K =1,NZ
      M=I*24 - 24+1
     SMO =SM12(M,K) + SM36(M,K)
     K36 = 0.99162 - 0.01522*GI(I) - 0.00006*SMO + 0.00290*PE(I)
       TS=36.0
       TW=12.0
     BO = K36 -0.01916*DLOG(TS )
     K12 = BO +0.01916*DLOG(TW )
C     K36 = DEPLETION CONSTANT FOR 0 - 36 INCH ZONE
C     BO  = DEPLETION CONSTANT DEPTH INTERCEPT
C     K12 = DEPLETION CONSTANT FOR 0 - 12 INCH ZONE
     SME12(I+1) = K12*SM12(M,K)
     SM36E(I+1) = K36*SMO
     SME36(I+1) = SM36E(I+1)- SME12(I+1)
     ET12(I,K) = SM12(M,K) - SME12(I+1)
     ET36(I,K) = SM36(M,K) - SME36(I+1)
      IF(ET12(I,K).LE.0.0) ET12(I,K)=0.02
      IF(ET36(I,K).LE.0.0) ET36(I,K)=0.0
     DO 104 J = 1,24
C     HOURLY COMPUTATIONS
C     DAILY COMPUTATIONS
C     J1 TO J8  INDEX FOR UNKNOWN PARAMETERS STARTING FROM ZONE 1
     IF(K.EQ.1) J1=1
     IF(K.EQ.1) J2=2
     IF(K.EQ.1) J3=3
     IF(K.EQ.1) J4=4
     IF(K.EQ.2) J1=5
     IF(K.EQ.2) J2=6
     IF(K.EQ.2) J3=7
     IF(K.EQ.2) J4=8
     M = I*24 + J-24
     ETH12(M,K)  = ET12(I,K)*ETH(J)
     ETH36(M,K) = ET36(I,K)*ETH(J)
C     0 - 12 INCH ZONE COMPUTATIONS
     IF(SM12(M,K).LE.SMC12(K)) PERC(M,K) = 0.0
     IF(SM12(M,K).LE.SMC12(K)) GO TO 200
      PERC(M,K) = SM12(M,K)-SMC12(K)-COE(J1)*DTANH(COE(J2)*(SM12(M,K) -
    1 SMC12(K)))
      IF(PERC(M,K).LT.0.0) PERC(M,K)=0.0
  200 SM12(M+1,K) =RAIN(M)+SM12(M,K)-ETH12(M,K)-PERC(M,K)
C     12 - 36 INCH ZONE COMPUTATIONS
     IF(SM36(M,K).LE.SMC36(K)) RUN(M,K) = 0.0
     IF(SM36(M,K).LE.SMC36(K)) GO TO 201
      RUN(M,K) =(SM36(M,K)-SMC36(K)-COE(J3)*DTANH(COE(J4)*(SM36(M,K)-
    1 SMC36(K))))*1.0
       IF(RUN(M,K).LE.0.0) RUN(M,K)=0.0
  201 CONTINUE
       MJ=M-1
      MJ1=M-2
       IF(M.EQ.1.OR.M.EQ.2)
    1 RUN(M,K)=PAR(5)*RUN(M,K)
       IF(M.EQ.1.OR.M.EQ.2) GO TO 400
       RUNA=RUN(MJ1,K) +0.020*RUN(MJ1,K)
     IF(RUN(MJ,K).GE.RUNA)
    1 RUN(M,K)=PAR(5)*RUN(M,K)
     IF(RUN(MJ,K).LT.RUNA)
    1 RUN(M,K)=PAR(6)*RUN(M,K)
  400   CONTINUE
       DS=0.0
       IF(RUN(M,K).GT.0.0) DS=0.001
     IF(K.EQ.1) SM36(M+1,K) =SM36(M,K)+PERC(M,K)-RUN(M,K)-ETH36(M,K)
    1 -DS
     IF(K.EQ.1) GO TO 203
     SM36(M+1,K) =SM36(M,K)+PERC(M,K)-RUN(M,K)+(RUN(M,K-1))*AREA(1)
    1 -ETH36(M,K)-DS
      RUN(M,2) = RUN(M,2) *AREA(2)
  203 CONTINUE
     IF(K.EQ.NZ) PREDY(M) =RUN(M,K)
  104 CONTINUE
  103 CONTINUE
  102 CONTINUE
     IF(ISTART.EQ.2) WRITE(6,60)ITERAT
   60 FORMAT('0 MODEL WAS EVALUATED',I8,'    TIMES')
     RETURN
     END
C     LIMIT FOR PATSEAR
     SUBROUTINE LIMIT(PAR,LPAR,NPAR,ISTART)
     IMPLICIT REAL*8(A-H,O-Z)
     DIMENSION PAR(20),LPAR(20)
       IF(ISTART.EQ.0) GO TO 40
       IF(ISTART.EQ.2) GO TO 40
       READ(5,2) WL1,WL2,WL3,WL4,WL5,WL6,WL7,WL8,W11,W12,W13,W14,W15,
    1W16,W17,W18
     WRITE(6,500) WL1,W11,WL2,W12,WL3,W13,WL4,W14,WL5,W15,WL6,W16,
    1WL7,W17,WL8,W18
  500   FORMAT(/,'  LIMITS ',8(' , ',F5.2,' -',F5.2),/)
    2  FORMAT(16F5.2)
   40  CONTINUE
       IF(PAR(1).LE.WL1.AND.PAR(1).GE.W11) GO TO 20
      I=1
      WRITE(6,10) I
      LPAR(I)=1
   20  CONTINUE
       IF(PAR(2).LE.WL2.AND.PAR(2).GE.W12) GO TO 21
      I=2
      LPAR(I)=1
      WRITE(6,10) I
   21 CONTINUE
       IF(PAR(3).LE.WL3.AND.PAR(3).GE.W13) GO TO 22
      I=3
      LPAR(I)=1
      WRITE(6,10) I
   22 CONTINUE
       IF(PAR(4).LE.WL4.AND.PAR(4).GE.W14) GO TO 23
```

```
      I=4
      LPAR(I)=1
      WRITE(6,10) I
   23 CONTINUE
       IF(PAR(5).LE.WL5.AND.PAR(5).GE.W15) GO TO 24
      I=5
      WRITE(6,10) I
      LPAR(I)=1
   24 CONTINUE
       IF(PAR(6).LE.WL6.AND.PAR(6).GE.W16) GO TO 25
      I=6
      WRITE(6,10) I
      LPAR(I)=1
   25 CONTINUE
   10  FORMAT('     ***** PARAMETER',I5,'    ON LIMIT')
      RETURN
      END
C     READ IN OR COMPUTE WEIGHTING FACTORS
      SUBROUTINE WGTING(ISTART,NOBS)
      IMPLICIT REAL*8(A-H,O-Z)
       DIMENSION WGT(1700),OBSY(1700),PREDY(1700),TPAR(20),ERR(1700)
      DIMENSION ETH12(1700,2),ETH36(1700,2),SM12(1700,2),SM36(1700,2),
     1PERC(1700,2),RUN(1700,2),RAIN(1700)
       COMMON ETH12,ETH36,SM12,SM36,PERC,RUN,RAIN
      COMMON OBSY,PREDY,TPAR,ERR,WGT
C
C     THIS IS PRESENTLY A DUMMY.
C
      RETURN
      END
       SUBROUTINE WBC(NOBS)
C     COMPUTE ALL COMPONENTS OF THE WATER BALANCE
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION ETH12(1700,2),ETH36(1700,2),SM12(1700,2),SM36(1700,2),
     1PERC(1700,2),RUN(1700,2),RAIN(1700)
        DIMENSION PREDY(1700) ,TITLE(10)
        DIMENSION OBSY(1700),TPAR(20),ERR(1700),WGT(1700)
       COMMON ETH12,ETH36,SM12,SM36,PERC,RUN,RAIN
      COMMON OBSY,PREDY,TPAR,ERR ,WGT,TITLE
       PERC1=0.0
       PERC2=0.0
       RUN1T=0.0
       RUN2T=0.0
       RUNAT=0.0
       ET121 =0.0
       ET122 =0.0
            ET361=0.0
            ET362=0.0
       RAT=0.0
   10  FORMAT(5X,'TOTAL',D13.5,D13.5,13X,2D13.5,13X,D13.5)
   11  FORMAT(5X,'TOTAL',D13.5, D13.5,13X,3D13.5,13X,2D13.5)
       NZ=2
       DO 100 K=1,NZ
    2  FORMAT(1H1,5X,10A8,/,'      ZONE - ',I2)
        IM=49
       DO 100 M=1,NOBS
       IF(K.EQ.NZ) GO TO 200
        IM=IM+1
       IF(IM.EQ.50) WRITE(6,2) (TITLE(MM),MM=1,10),K
       IF(IM.EQ.50)WRITE(6,3)
       IF(IM.EQ.50) IM=1
    3  FORMAT('     HOURS     RAIN          ET12            SM12             PERC
     1          ET36            SM36           FLOW')
    4  FORMAT(5X,I5,7D13.5)
       WRITE(6,4) M,RAIN(M),ETH12(M,K),SM12(M,K),PERC(M,K),ETH36(M,K),
     1SM36(M,K),RUN(M,K)
       PERC1=PERC1+PERC(M,1)
       RUN1T=RUN1T+RUN(M,1)
        ET121=ET121+ETH12(M,1)
       ET361=ET361+ETH36(M,1)
       RAT=RAT+RAIN(M)
       IF(M.EQ.NOBS) WRITE(6,10)RAT, ET121,PERC1,ET361,RUN1T
        GO TO 100
  200  CONTINUE
       IF(M.EQ.1) IM=49
       IM=IM+1
       IF(IM.EQ.50) WRITE(6,2) (TITLE(MM),MM=1,10),K
       IF(IM.EQ.50) WRITE(6,5)
       IF(IM.EQ.50) IM=1
    5  FORMAT('     HOURS     RAIN          ET12            SM12             PERC
     1          FLOW1           ET36            SM36            FLOW        ACT FLOW
     2  ')
    6  FORMAT(5X,I5,9D13.5)
       WRITE(6,6) M,RAIN(M),ETH12(M,K),SM12(M,K),PERC(M,K),
     1RUN(M,K-1),ETH36(M,K),SM36(M,K),RUN(M,K),OBSY(M)
       PERC2=PERC2+PERC(M,2)
       RUN2T=RUN2T+RUN(M,2)
       RUNAT=RUNAT+OBSY(M)
        ET122=ET122+ETH12(M,2)
       ET362=ET362+ETH36(M,2)
  100  CONTINUE
       WRITE(6,11) RAT,ET122,PERC2,RUN1T,ET362,RUN2T,RUNAT
       WRITE(6,400)
  400  FORMAT(1H1)
       CALL PLOT(NOBS)
       RETURN
       END
      SUBROUTINE PLOT(NOBS)
C     PLOT OBSERVED AND PREDICTED HYDROGRAPHS
      IMPLICIT REAL*8(A-H,O-Z)
        REAL*4 OBS,X,PRED
      DIMENSION PAR(20),BPAR(20),TPAR(20),OBSY(1700),PREDY(1700),
     1TITLE(10),SS(2),LPAR(20),DR(20),IEXPLR(20),PCT(20),D(20),CHANGE(20
     2),ERR(1700) ,WGT(1700)
      DIMENSION ETH12(1700,2),ETH36(1700,2),SM12(1700,2),SM36(1700,2),
     1PERC(1700,2),RUN(1700,2),RAIN(1700)
       COMMON ETH12,ETH36,SM12,SM36,PERC,RUN,RAIN
      COMMON OBSY,PREDY,TPAR,ERR ,WGT,TITLE
      DIMENSION PRED(1700),X(1700),Z(200)
       DIMENSION OBS(1700)
```

```
      DO 1 I=1,NOBS
      X(I)=I
      OBS(I)=OBSY(I)
    1 PRED(I)=RUN(I,2)
       JJ=0
  100 CONTINUE
     JJ=JJ+1
      CALL MODESG(Z,0)
      CALL GRAPHG(Z,NOBS,X,OBS,12,12HTIME (HOURS),17,17HDISCHARGE (IN/H
     1R) ,80,TITLE)
       CALL SETSMG(Z,30,4.0)
      CALL LINESG(Z,NOBS,X,OBS)
      CALL POINTG(Z,NOBS,X,PRED)
       CALL SETSMG(Z,31,1.0)
      CALL LINESG(Z,NOBS,X,PRED)
      IF(JJ.NE.2) GO TO 100
       CALL PAGEG(Z,0,0,1)
      CALL EXITG(Z)
      RETURN
       END
```

```
********** SAMPLE TWO PARAMETER PROGRAM INPUT *********

 1
  STATION 2 SUBSURFACE FLOW EVENT 1 NOVEMBER 29,1968 TO DECEMBER 6,1968
 2  168  100    10.001 0.50
   0.50       0.50
 0    0
   0.02       0.02
0.51 0.52
1.23 5.50 1.62 6.50 0.50 1.00
 7  0  7
 1.09  5.95  2.20  6.39

0.12 0.14 0.06 0.03 0.07 0.03 0.09 0.11
112968
113068
 120168                                                           10 40 31
120268
 120368                 10 10 18 10 10 10 10 20 10 10 10 10 15
120468
120568
 701 12 468 1 .3926E-03 .1262E-02 .1567E-02 .1724E-02 .1752E-02 .1794E-02
 701 12 468 2 .1700E-02 .1676E-02 .1609E-02 .1596E-02 .1569E-02 .1586E-02
 701 12 468 3 .1563E-02 .1525E-02 .1506E-02 .1351E-02 .1316E-02 .1203E-02
 701 12 468 4 .1097E-02 .1022E-02 .9392E-03 .8664E-03 .7721E-03 .7593E-03
 701 12 568 1 .6991E-03 .6673E-03 .5876E-03 .5066E-03 .4598E-03 .4096E-03
 701 12 568 2 .3406E-03 .2623E-03 .2056E-03 .1358E-03 .1037E-03 .8488E-04
 701 12 568 3 .1053E-03 .1336E-03 .1176E-03 .8214E-04 .4757E-04 .1835E-04
 701 12 568 4 .2722E-050.        0.        0.        0.        0.
```

SAMPLE OUTPUT

```
                         PATTERN SEARCH FOR OPTIMUM OF OBJECTIVE FUNCTION
                            STATION Z SUBSURFACE FLOW EVENT 1 NOVEMBER 29,1968 TO DECEMBER 6,1968
                       IOPT=  1    OPTIMIZE ON THE FOLLOWING
             1-SSE      2-WEIGHTED SSE       3-SUM OF ABSOLUTE ERRORS       4-SUM OF PREDICTIONS

LIMITS  ,  0.51 - 0.0  ,  0.52 - 0.0  ,  0.0  - 0.0  ,  0.0  - 0.0  ,  0.0  - 0.0  ,  0.0  - 0.0  ,  0.0  - 0.0  ,  0.0  - 0.0

SMC12(1) -  1.23   SMC36(1) -  5.50   SMC12(2) -  1.62   SMC36(2) -  6.50   AREA(1) -  0.50   AREA(2) -   1.00

DECREMENTERS FOR DELTAS
1 0.50  2 0.50

NROUND          SS      IACEL             PARAMETERS
  0      0.28525130D-02  0                 1      0.50000  2       0.50000
  1      0.28525130D-02  0                 1      0.50000  2       0.50000
           DELTAS AT BEGINNING OF ROUND
              1  0.02000000  2  0.02000000
  **** PARAMETER    1  ON LIMIT
       1       0.28525130D-02      0.30970867D-02       0.10000000D 01
       2       0.28525130D-02      0.33318821D-02       0.23037633D-02
  **** PARAMETER    2  ON LIMIT
  1      C.23037633D-02  1                 1      0.50000  2       0.52000
  2      C.23037633D-02  1                 1      0.50000  2       0.52000
           DELTAS AT BEGINNING OF ROUND
              1  0.01000000  2  0.02000000
       1       0.23037633D-02      0.24120953D-02       0.22995222D-02
  **** PARAMETER    2  ON LIMIT
       2       0.22995222D-02      0.27706686D-02       0.10000000D 01
  **** PARAMETER    1  ON LIMIT
  2      0.22995222D-02  1                 1      0.51000  2       0.52000
  3      0.22995222D-02  1                 1      0.51000  2       0.52000
           DELTAS AT BEGINNING OF ROUND
              1  0.01000000  2  0.01000000
  **** PARAMETER    1  ON LIMIT
       1       C.22995222D-02      0.23037633D-02       0.10000000D 01
  **** PARAMETER    2  ON LIMIT
       2       0.22995222D-02      0.24999C74D-02       0.10000000D 01
  4      C.22995222D-02  0                 1      0.51000  2       0.52000
           DELTAS AT BEGINNING OF ROUND
              1  C.01000000  2  0.01000000
  **** PARAMETER    1  ON LIMIT
       1       0.22995222D-02      0.23037633D-02       0.10000000D 01
  **** PARAMETER    2  ON LIMIT
       2       0.22995222D-02      0.24999074D-02       0.10000000D 01
  4      0.22995222D-02  0                 1      0.51000  2       0.52000
           DELTAS AT BEGINNING OF ROUND
              1  0.00500000  2  0.00500000
       1       0.22995222D-02      0.22757139D-02       0.10000000D 01
  **** PARAMETER    2  ON LIMIT
       2       0.22757139D-02      0.24104340D-02       0.10000000D 01
  4      C.23037633D-02  1                 1      0.50000  2       0.52000
  5      0.22757139D-02  1                 1      0.50000  2       0.52000
           DELTAS AT BEGINNING OF ROUND
              1  0.00500000  2  0.00250000
       1       C.22757139D-02      0.23569703D-02       0.22757139D-02
  **** PARAMETER    2  ON LIMIT
       2       C.22757139D-02      0.23707576D-02       0.10000000D 01
  6      0.22757139D-02  0                 1      0.50500  2       0.52000
           DELTAS AT BEGINNING OF ROUND
              1  0.00500000  2  0.00250000
       1       0.22757139D-02      0.23037633D-02       0.22995222D-02
  **** PARAMETER    2  ON LIMIT
```

PATTERN SEARCH FOR OPTIMUM OF OBJECTIVE FUNCTION
STATION Z SUBSURFACE FLOW EVENT 1 NOVEMBER 29,1968 TO DECEMBER 6,1968
IOPT= 1 OPTIMIZE ON THE FOLLOWING
1-SSE 2-WEIGHTED SSE 3-SUM OF ABSOLUTE ERRORS 4-SUM OF PREDICTIONS

	OBSERVED	PREDICTED	ERROR
1	0.0	0.0	0.0
2	0.0	0.0	0.0
3	0.0	0.0	0.0
4	0.0	0.0	0.0
5	0.0	0.0	0.0
6	0.0	0.0	0.0
7	0.0	0.0	0.0
8	0.0	0.0	0.0
9	0.0	0.0	0.0
10	0.0	0.0	0.0
11	0.0	0.0	0.0
12	0.0	0.0	0.0
13	0.0	0.0	0.0
14	0.0	0.0	0.0
15	0.0	0.0	0.0
16	0.0	0.0	0.0
17	0.0	0.0	0.0
18	0.0	0.0	0.0
19	0.0	0.0	0.0
20	0.0	0.0	0.0
21	0.0	0.0	0.0
22	0.0	0.0	0.0
23	0.0	0.0	0.0
24	0.0	0.0	0.0
25	0.0	0.0	0.0
26	0.0	0.0	0.0
27	0.0	0.0	0.0
28	0.0	0.0	0.0
29	0.0	0.0	0.0
30	0.0	0.0	0.0
31	0.0	0.0	0.0
32	0.0	0.0	0.0
33	0.0	0.0	0.0
34	0.0	0.0	0.0
35	0.0	0.0	0.0
36	0.0	0.0	0.0
37	0.0	0.0	0.0
38	0.0	0.0	0.0
39	0.0	0.0	0.0
40	0.0	0.0	0.0
41	0.0	0.0	0.0
42	0.0	0.0	0.0
43	0.0	0.0	0.0
44	0.0	0.0	0.0
45	0.0	0.0	0.0
46	0.0	0.0	0.0
47	0.0	0.0	0.0
48	0.0	0.0	0.0
49	0.0	0.0	0.0
50	0.0	0.0	0.0
51	0.0	0.0	0.0
52	0.0	0.0	0.0
53	0.0	0.0	0.0
54	0.0	0.0	0.0
55	0.0	0.0	0.0
56	0.0	0.0	0.0
57	0.0	0.0	0.0
58	0.0	0.0	0.0

124	[illegible]	[illegible]	[illegible]
125	0.20258D-02	0.64346D-02	-0.44048D-02
126	0.20785D-02	0.65405D-02	-0.44620D-02
127	0.19696D-02	0.66276D-02	-0.46580D-02
128	0.19418D-02	0.67395D-02	-0.47977D-02
129	0.18641D-02	0.68313D-02	-0.49672D-02
130	0.16491D-02	0.66572D-02	-0.50082D-02
131	0.18178D-02	0.68609D-02	-0.50431D-02
132	0.18375D-02	0.68445D-02	-0.50070D-02
133	0.18108D-02	0.68097D-02	-0.49988D-02
134	0.17668D-02	0.67588D-02	-0.49920D-02
135	0.17448D-02	0.66950D-02	-0.49502D-02
136	0.16116D-02	0.66284D-02	-0.50169D-02
137	0.15247D-02	0.65683D-02	-0.50436D-02
138	0.13938D-02	0.65183D-02	-0.51245D-02
139	0.12710D-02	0.64791D-02	-0.52081D-02
140	0.11841D-02	0.64457D-02	-0.52617D-02
141	0.10881D-02	0.64127D-02	-0.53246D-02
142	0.10038D-02	0.63800D-02	-0.53762D-02
143	0.89453D-03	0.63476D-02	-0.54530D-02
144	0.87970D-03	0.63154D-02	-0.54357D-02
145	0.80996D-03	0.62836D-02	-0.54736D-02
146	0.77311D-03	0.62520D-02	-0.54789D-02
147	0.68078D-03	0.62206D-02	-0.55399D-02
148	0.58693D-03	0.61895D-02	-0.56026D-02
149	0.53271D-03	0.61586D-02	-0.56259D-02
150	0.47455D-03	0.61280D-02	-0.56534D-02
151	0.39461D-03	0.60975D-02	-0.57029D-02
152	0.30389D-03	0.60651D-02	-0.57612D-02
153	0.23820D-03	0.60272D-02	-0.57890D-02
154	0.15733D-03	0.59812D-02	-0.58239D-02
155	0.12014D-03	0.59283D-02	-0.58081D-02
156	0.98339D-04	0.58710D-02	-0.57727D-02
157	0.12200D-03	0.58103D-02	-0.56883D-02
158	0.15478D-03	0.57476D-02	-0.55928D-02
159	0.13625D-03	0.56846D-02	-0.55483D-02
160	0.95165D-04	0.56238D-02	-0.55286D-02
161	0.55113D-04	0.55693D-02	-0.55142D-02
162	0.21260D-04	0.55254D-02	-0.55041D-02
163	0.31536D-05	0.54926D-02	-0.54894D-02
164	0.0	0.54658D-02	-0.54658D-02
165	0.0	0.54391D-02	-0.54391D-02
166	0.0	0.54125D-02	-0.54125D-02
167	0.0	0.53860D-02	-0.53860D-02
168	0.0	0.53596D-02	-0.53596D-02

** CONVERGED ROUND= 9 TEST= 0.00100 SSB= 0.22360256D-02

PARAMETERS

1 0.5025 2 0.5143

STATISTICS

SY= 0.43049844D-01 SSY= 0.65381581D-04 SX= 0.38325396D 00 SSX= 0.28019399D-02

SXY= 0.31564794D-03 SSE= 0.22360256D-02 ATSS= 0.54350099D-04 ASSR=-0.21816755D-02

MEAN OBS= 0.25624907D-03 MEAN PRED= 0.22812736D-02 CORCO= 0.50125 SDEV= 0.36701544D-02

COEVAR= 0.14322606D 02 SEREST= 0.36482429D-02

STATION 2 SUBSURFACE FLOW EVENT 1 NOVEMBER 29,1968 TO DECEMBER 6,1968

ZONE - 1

HOURS	RAIN	ET12	SM12	PERC	ET36	SM36	FLOW
1	0.0	0.0	0.10900D 01	0.0	0.0	0.59500D 01	0.0
2	0.0	0.0	0.10900D 01	0.0	0.0	0.59500D 01	0.0
3	0.0	0.0	0.10900D 01	0.0	0.0	0.59500D 01	0.0
4	0.0	0.0	0.10900D 01	0.0	0.0	0.59500D 01	0.0
5	0.0	0.0	0.10900D 01	0.0	0.0	0.59500D 01	0.0
6	0.0	0.0	0.10900D 01	0.0	0.0	0.59500D 01	0.0
7	0.0	0.26049D-03	0.10900D 01	0.0	0.22162D-03	0.59500D 01	0.0
8	0.0	0.94870D-03	0.10897D 01	0.0	0.80713D-03	0.59498D 01	0.0
9	0.0	0.19489D-02	0.10888D 01	0.0	0.16580D-02	0.59490D 01	0.0
10	0.0	0.28429D-02	0.10868D 01	0.0	0.24187D-02	0.59473D 01	0.0
11	0.0	0.34217D-02	0.10840D 01	0.0	0.29111D-02	0.59449D 01	0.0
12	0.0	0.38945D-02	0.10806D 01	0.0	0.33133D-02	0.59420D 01	0.0
13	0.0	0.42097D-02	0.10767D 01	0.0	0.35815D-02	0.59387D 01	0.0
14	0.0	0.43158D-02	0.10725D 01	0.0	0.36718D-02	0.59351D 01	0.0
15	0.0	0.41067D-02	0.10682D 01	0.0	0.34939D-02	0.59314D 01	0.0
16	0.0	0.33671D-02	0.10641D 01	0.0	0.28646D-02	0.59279D 01	0.0
17	0.0	0.21064D-02	0.10607D 01	0.0	0.17921D-02	0.59251D 01	0.0
18	0.0	0.73645D-03	0.10586D 01	0.0	0.62655D-03	0.59233D 01	0.0
19	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
20	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
21	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
22	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
23	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
24	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
25	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
26	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
27	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
28	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
29	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
30	0.0	0.0	0.10578D 01	0.0	0.0	0.59226D 01	0.0
31	0.0	0.25228D-03	0.10578D 01	0.0	0.22227D-03	0.59226D 01	0.0
32	0.0	0.91879D-03	0.10576D 01	0.0	0.80952D-03	0.59224D 01	0.0
33	0.0	0.18874D-02	0.10567D 01	0.0	0.16629D-02	0.59216D 01	0.0
34	0.0	0.27532D-02	0.10548D 01	0.0	0.24258D-02	0.59199D 01	0.0
35	0.0	0.33139D-02	0.10520D 01	0.0	0.29198D-02	0.59175D 01	0.0
36	0.0	0.37717D-02	0.10487D 01	0.0	0.33231D-02	0.59146D 01	0.0
37	0.0	0.40769D-02	0.10449D 01	0.0	0.35921D-02	0.59113D 01	0.0
38	0.0	0.41797D-02	0.10409D 01	0.0	0.36826D-02	0.59077D 01	0.0
39	0.0	0.39773D-02	0.10367D 01	0.0	0.35043D-02	0.59040D 01	0.0
40	0.0	0.32609D-02	0.10327D 01	0.0	0.28731D-02	0.59005D 01	0.0
41	0.0	0.20400D-02	0.10294D 01	0.0	0.17974D-02	0.58976D 01	0.0
42	0.0	0.71323D-03	0.10274D 01	0.0	0.62841D-03	0.58958D 01	0.0
43	0.0	0.0	0.10267D 01	0.0	0.0	0.58952D 01	0.0
44	0.0	0.0	0.10267D 01	0.0	0.0	0.58952D 01	0.0
45	0.0	0.0	0.10267D 01	0.0	0.0	0.58952D 01	0.0
46	0.0	0.0	0.10267D 01	0.0	0.0	0.58952D 01	0.0
47	0.0	0.0	0.10267D 01	0.0	0.0	0.58952D 01	0.0
48	0.0	0.0	0.10267D 01	0.0	0.0	0.58952D 01	0.0
49	0.0	0.0	0.10267D 01	0.0	0.0	0.58952D 01	0.0

STATION Z SUBSURFACE FLOW EVENT 1 NOVEMBER 29,1968 TO DECEMBER 6,1968

ZONE - 1

HOURS	RAIN	ET12	SM12	PERC	ET36	SM36	FLOW
148	0.G	0.0	0.15344D 01	0.37704D-02	0.0	0.71488D 01	0.69058D-02
149	0.C	0.0	0.15306D 01	0.36514D-02	0.0	0.71456C 01	0.68698D-02
150	0.0	0.0	0.15269D 01	0.35386D-02	0.0	0.71424D 01	0.68329D-02
151	C.C	0.37191D-03	0.15234D 01	0.34317D-02	0.23732D-03	0.71391D 01	0.67952D-02
152	G.0	0.13545D-02	0.15196D 01	0.33194D-02	0.86432D-03	0.71355D 01	0.67542D-02
153	0.0	0.27825D-02	0.15149D 01	0.31849D-02	0.17755D-02	0.71312D 01	0.67053D-02
154	G.G	0.40589D-02	0.15090D 01	0.30188D-02	0.25900D-02	0.71259D 01	0.66454D-02
155	0.0	0.48854D-C2	0.15019D 01	0.28300D-02	0.31174D-02	0.71197D 01	0.65754D-02
156	0.0	0.55603D-02	0.14942D 01	0.26338D-02	0.35481D-02	0.71129D 01	0.64985D-02
157	0.0	0.60103D-02	0.14860D 01	0.24363D-02	0.38352D-02	0.71054D 01	0.64159D-02
158	0.0	0.61618D-02	0.14775D 01	0.22440D-02	0.39319D-02	0.70976D 01	0.63295D-02
159	C.0	0.58634D-02	0.14691D 01	0.20638D-02	0.37415D-02	0.70896D 01	0.62414D-02
160	0.0	0.48073D-02	0.14612D 01	0.19036D-02	0.30676D-02	0.70817D 01	0.61551D-02
161	0.0	0.30075D-02	0.14545D 01	0.17752D-02	0.19191D-02	0.70744D 01	0.60758D-02
162	0.G	0.10515D-02	0.14497D 01	0.16876D-02	0.67095D-03	0.70682D 01	0.60088D-02
163	0.0	0.0	0.14470D 01	0.16388D-02	0.0	0.70632D 01	0.59553D-02
164	0.0	0.0	0.14453D 01	0.16102D-02	0.0	0.70588D 01	0.59092D-02
165	0.0	0.0	0.14437D 01	0.15824D-02	0.0	0.70545D 01	0.58635D-02
166	0.0	0.0	0.14421D 01	0.15554D-02	0.0	0.70503D 01	0.58182D-02
167	G.0	0.0	0.14406D 01	0.15292D-02	0.0	0.70460D 01	0.57733D-02
168	0.0	0.0	0.14390D 01	0.15038D-02	0.0	0.70418D 01	0.57287D-02
TOTAL	0.23500D 01	0.29388D 00		0.17086D 01	0.17136D 00		0.44969D 00

STATION 2 SUBSURFACE FLOW EVENT 1 NOVEMBER 29,1968 TO DECEMBER 6,1968

ZONE - 2

HOURS	RAIN	ET12	SM12	PERC	FLOW1	ET36	SM36	FLOW	ACT FLOW
1	0.0	0.0	0.22000D 01	0.0	0.0	0.0	0.63900D 01	0.0	0.0
2	0.0	0.0	0.22000D 01	0.0	0.0	0.0	0.63900D 01	0.0	0.0
3	0.0	0.0	0.22000D 01	0.0	0.0	0.0	0.63900D 01	0.0	0.0
4	0.0	0.0	0.22000D 01	0.0	0.0	0.0	0.63900D 01	0.0	0.0
5	0.0	0.0	0.22000D 01	0.0	0.0	0.0	0.63900D 01	0.0	0.0
6	0.0	0.0	0.22000D 01	0.0	0.0	0.0	0.63900D 01	0.0	0.0
7	0.0	0.52742D-03	0.22000D 01	0.0	0.0	0.67308D-04	0.63900D 01	0.0	0.0
8	0.0	0.19208D-02	0.21995D 01	0.0	0.0	0.24513D-03	0.63899D 01	0.0	0.0
9	0.0	0.39459D-02	0.21976D 01	0.0	0.0	0.50357D-03	0.63897D 01	0.0	0.0
10	0.0	0.57560D-02	0.21936D 01	0.0	0.0	0.73457D-03	0.63892D 01	0.0	0.0
11	0.0	0.69280D-02	0.21878D 01	0.0	0.0	0.88415D-03	0.63884D 01	0.0	0.0
12	0.0	0.78852D-02	0.21809D 01	0.0	0.0	0.10063D-02	0.63876D 01	0.0	0.0
13	0.0	0.85233D-02	0.21730D 01	0.0	0.0	0.10877D-02	0.63866D 01	0.0	0.0
14	0.0	0.87382D-02	0.21645D 01	0.0	0.0	0.11152D-02	0.63855D 01	0.0	0.0
15	0.0	0.83150D-02	0.21558D 01	0.0	0.0	0.10611D-02	0.63844D 01	0.0	0.0
16	0.0	0.68174D-02	0.21475D 01	0.0	0.0	0.87002D-03	0.63833D 01	0.0	0.0
17	0.0	0.42649D-02	0.21406D 01	0.0	0.0	0.54428D-03	0.63824D 01	0.0	0.0
18	0.0	0.14911D-02	0.21364D 01	0.0	0.0	0.19029D-03	0.63819D 01	0.0	0.0
19	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
20	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
21	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
22	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
23	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
24	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
25	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
26	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
27	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
28	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
29	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
30	0.0	0.0	0.21349D 01	0.0	0.0	0.0	0.63817D 01	0.0	0.0
31	0.0	0.51073D-03	0.21349D 01	0.0	0.0	0.74609D-04	0.63817D 01	0.0	0.0
32	0.0	0.18601D-02	0.21344D 01	0.0	0.0	0.27172D-03	0.63816D 01	0.0	0.0
33	0.0	0.38210D-02	0.21325D 01	0.0	0.0	0.55819D-03	0.63813D 01	0.0	0.0
34	0.0	0.55739D-02	0.21287D 01	0.0	0.0	0.81425D-03	0.63808D 01	0.0	0.0
35	0.0	0.67088D-02	0.21231D 01	0.0	0.0	0.98005D-03	0.63800D 01	0.0	0.0
36	0.0	0.76357D-02	0.21164D 01	0.0	0.0	0.11154D-02	0.63790D 01	0.0	0.0
37	0.0	0.82536D-02	0.21088D 01	0.0	0.0	0.12057D-02	0.63779D 01	0.0	0.0
38	0.0	0.84617D-02	0.21005D 01	0.0	0.0	0.12361D-02	0.63767D 01	0.0	0.0
39	0.0	0.80518D-02	0.20921D 01	0.0	0.0	0.11762D-02	0.63754D 01	0.0	0.0
40	0.0	0.66016D-02	0.20840D 01	0.0	0.0	0.96439D-03	0.63743D 01	0.0	0.0
41	0.0	0.41300D-02	0.20774D 01	0.0	0.0	0.60332D-03	0.63733D 01	0.0	0.0
42	0.0	0.14439D-02	0.20733D 01	0.0	0.0	0.21093D-03	0.63727D 01	0.0	0.0
43	0.0	0.0	0.20718D 01	0.0	0.0	0.0	0.63725D 01	0.0	0.0
44	0.0	0.0	0.20718D 01	0.0	0.0	0.0	0.63725D 01	0.0	0.0
45	0.0	0.0	0.20718D 01	0.0	0.0	0.0	0.63725D 01	0.0	0.0
46	0.0	0.0	0.20718D 01	0.0	0.0	0.0	0.63725D 01	0.0	0.0
47	0.0	0.0	0.20718D 01	0.0	0.0	0.0	0.63725D 01	0.0	0.0
48	0.0	0.0	0.20718D 01	0.0	0.0	0.0	0.63725D 01	0.0	0.0
49	0.0	0.0	0.20718D 01	0.0	0.0	0.0	0.63725D 01	0.0	0.0

STATION 2 SUBSURFACE FLOW EVENT 1 NOVEMBER 29,1968 TO DECEMBER 6,1968

ZONE - 2

HOURS	RAIN	ET12	SM12	PERC	FLOW1	ET36	SM36	FLOW	ACT FLOW
148	0.0	0.0	0.22395D 01	0.0	0.69058D-02	0.0	0.81227D 01	0.61895D-02	0.58693D-03
149	0.0	0.0	0.22395D 01	0.0	0.68698D-02	0.0	0.81199D 01	0.61586D-02	0.53271D-03
150	0.0	0.0	0.22395D 01	0.0	0.68329D-02	0.0	0.81172D 01	0.61280D-02	0.47455D-03
151	0.0	0.54041D-03	0.22395D 01	0.0	0.67952D-02	0.19387D-03	0.81145D 01	0.60975D-02	0.39461D-03
152	0.0	0.19682D-02	0.22390D 01	0.0	0.67542D-02	0.70606D-03	0.81116D 01	0.60651D-02	0.30389D-03
153	C.0	0.40431D-02	0.22370D 01	0.0	0.67053D-02	0.14504D-02	0.81082D 01	0.60272D-02	0.23820D-03
154	0.0	0.58979D-02	0.22330D 01	0.0	0.66454D-02	0.21158D-02	0.81041D 01	0.59812D-02	0.15733D-03
155	C.0	0.70988D-02	0.22271D 01	0.0	0.65754D-02	0.25466D-02	0.80993D 01	0.59283D-02	0.12014D-03
156	G.C	0.80795D-02	0.22200D 01	0.0	0.64985D-02	0.28984D-02	0.80941D 01	0.58710D-02	0.98339D-04
157	0.0	0.87334D-02	0.22119D 01	0.0	0.64159D-02	0.31330D-02	0.80886D 01	0.58103D-02	0.12200D-03
158	0.0	0.89535D-02	0.22032D 01	0.0	0.63295D-02	0.32120D-02	0.80829D 01	0.57476D-02	0.15478D-03
159	0.0	0.85199D-02	0.21942D 01	0.0	0.62414D-02	0.30564D-02	0.80771D 01	0.56846D-02	0.13625D-03
160	0.0	0.69854D-02	0.21857D 01	0.0	0.61551D-02	0.25059D-02	0.80714D 01	0.56238D-02	0.95165D-04
161	0.0	0.43700D-02	0.21787D 01	0.0	0.60758D-02	0.15677D-02	0.80664D 01	0.55693D-02	0.55113D-04
162	0.0	0.15278D-02	0.21744D 01	0.0	0.60088D-02	0.54809D-03	0.80623D 01	0.55254D-02	0.21260D-04
163	0.0	0.0	0.21728D 01	0.0	0.59553D-02	0.0	0.80592D 01	0.54926D-02	0.31536D-05
164	0.0	0.0	0.21728D 01	0.0	0.59092D-02	0.0	0.80567D 01	0.54658D-02	0.0
165	0.0	0.0	0.21728D 01	0.0	0.58635D-02	0.0	0.80542D 01	0.54391D-02	0.0
166	0.0	0.0	0.21728D 01	0.0	0.58182D-02	0.0	0.80517D 01	0.54125D-02	0.0
167	0.0	0.0	0.21728D 01	0.0	0.57733D-02	0.0	0.80492D 01	0.53860D-02	0.0
168	0.0	0.0	0.21728D 01	0.0	0.57287D-02	0.0	0.80467D 01	0.53596D-02	0.0
TOTAL	0.23500D C1	0.47473D 00		0.19024D 01	0.44969D 00	0.89840D-01		0.38325D 00	0.43050D-01

APPENDIX D

EVAPOTRANSPIRATION

Over the three-year study period there were 26 intervals between soil moisture measurements during which it was thought that no vertical or horizontal drainage (moisture held at less than 0.3 bar tension) was occurring and no rainfall occurred. This data was used in the formulation of the equations relating to evapotranspiration. A data base of K_D's for various depths, D, was determined by substituting this data into equation 5. The determination of K_D is illustrated in Table D-1. The graphs of the depletion constant versus depth for each data set indicated a semilogarithmic relationship as is illustrated in Figure D-1. When the semilogarithmic relationship (equation 7) was fitted to the data, the shape coefficient remained fairly stable.

Table D-1. Example of Depletion Constant (K_D) Determination

	Accumulation Over Depth Soil Moisture 1/				
Depth (in)	4-23-70 (in)	4-24-70 (in)	Evapo-transpiration 2/ (in)	K_D 3/	K_D 4/
6	0.43	0.41	0.02	0.953	0.952
12	1.26	1.22	0.04	0.968	0.966
18	2.80	2.74	0.06	0.978	0.974
24	4.44	4.37	0.07	0.984	0.979
36	6.07	5.99	0.08	0.987 5/	0.987
48	9.33	9.24	0.09	0.990	0.992

1/ Measured soil moisture

2/ Evapotranspiration determined by substracting the 4-24-70 soil moisture from the 4-23-70 soil moisture.

3/ K_D was determined from equation 5 by substituting the soil moisture in column 2 and evapotranspiration in column 4.

4/ K_D was determined from equation 8 using K_D = 0.987 for the 36-inch depth.

5/ Equation 6 produced a K_{36} = 0.988

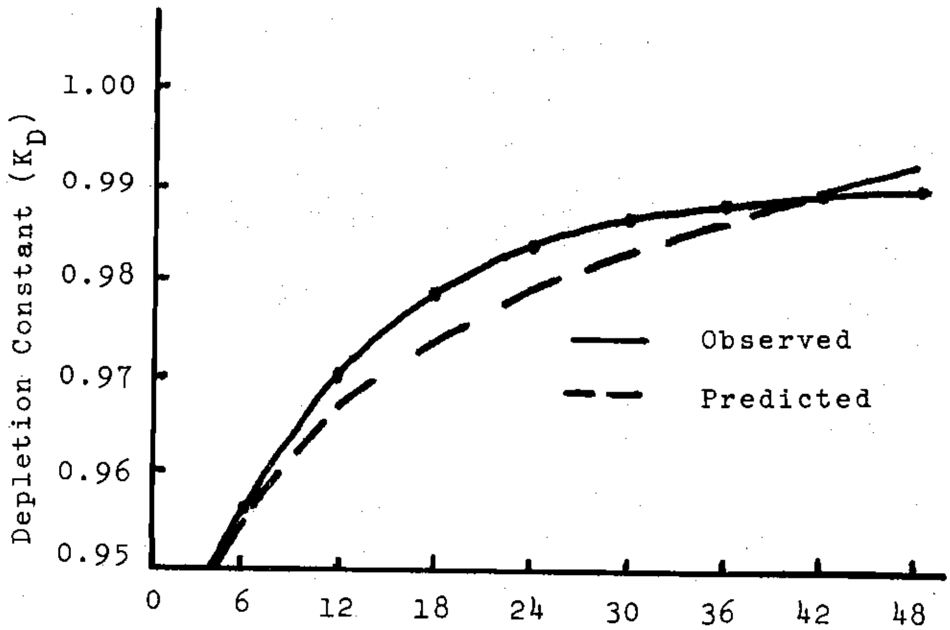

Figure D-1. Depletion Constant Versus Depth

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